Panchromatic Fourier Transform Spectrometer (PanFTS) for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission

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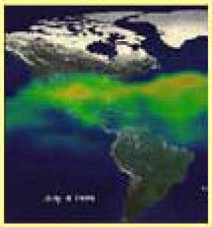
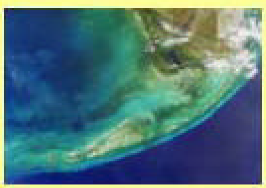
Decadal Survey Rationale for GEO-CAPE

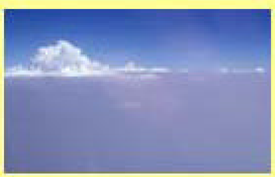
Scientific Objectives



Identification of human vs. natural sources for aerosols and ozone precursors



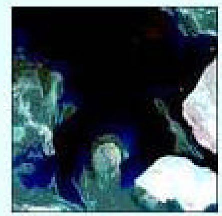
Dynamics of coastal ecosystems, river plumes, tidal fronts



Observation of air pollution transport in North, Central, and South America

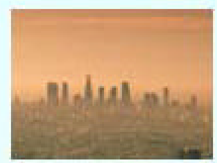
Societal Benefits

Predict track of oil spills, fires, and releases from environmental disasters



Detection and tracking water-borne hazardous materials

Coastal health



Air quality forecasts

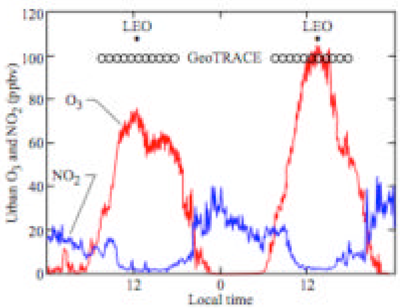
- **Geostationary Orbit:**
  - **Captures rapidly changing phenomena with high spatial resolution.**
- **Instruments for both atmospheric composition and ocean color**
  - **Atmospheric correction to obtain accurate water-leaving radiance.**
  - **Coupled air/sea trace gas exchange studies**

NRC Decadal Survey:
Observational Requirements

Atmospheric Science

- **Air Quality in Populated Areas**

  species: O_3, NO_2, CO, HCHO, $(CHO)_2$
  horizontal sampling: 5-10 km
  vertical sampling: total column
  temporal sampling: ~1 hour



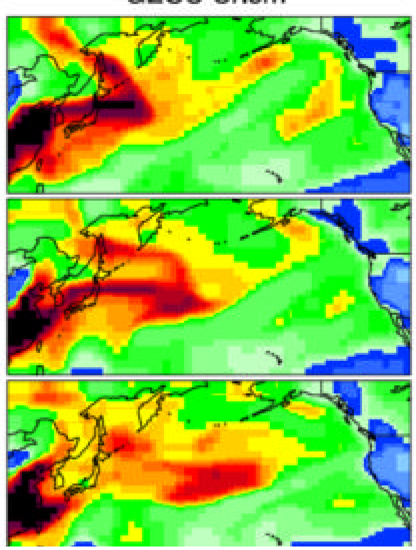
Diurnal variability of NO_2 and O_3 in urban smog

- **Long-range Transport of Air Pollution**

Transport of pollutants from Asia to North America and Europe requires high-density sampling.

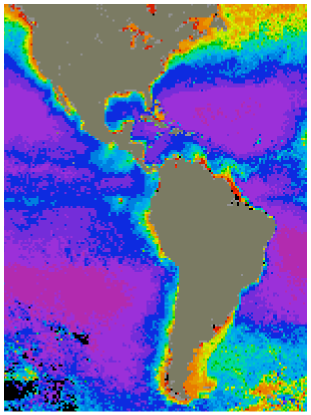
"Chemical weather"

GEOS-Chem

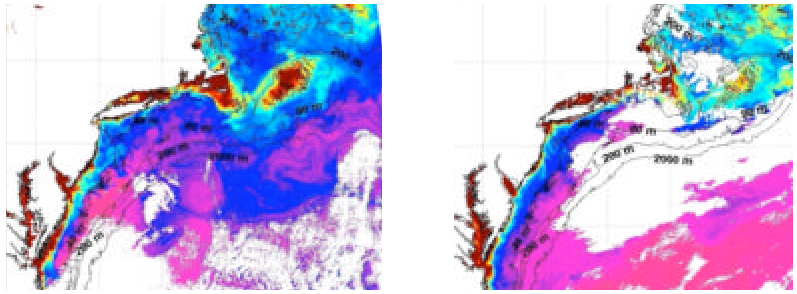


Ocean Science

- Sea Surface Reflectance measurements for
  - Concentration of chlorophyll, suspended and dissolved matter
  - Concentration of particulate inorganic carbon (PIC) and particulate organic carbon (POC)
  - Concentration of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) will be estimated from regionally-specific algorithms



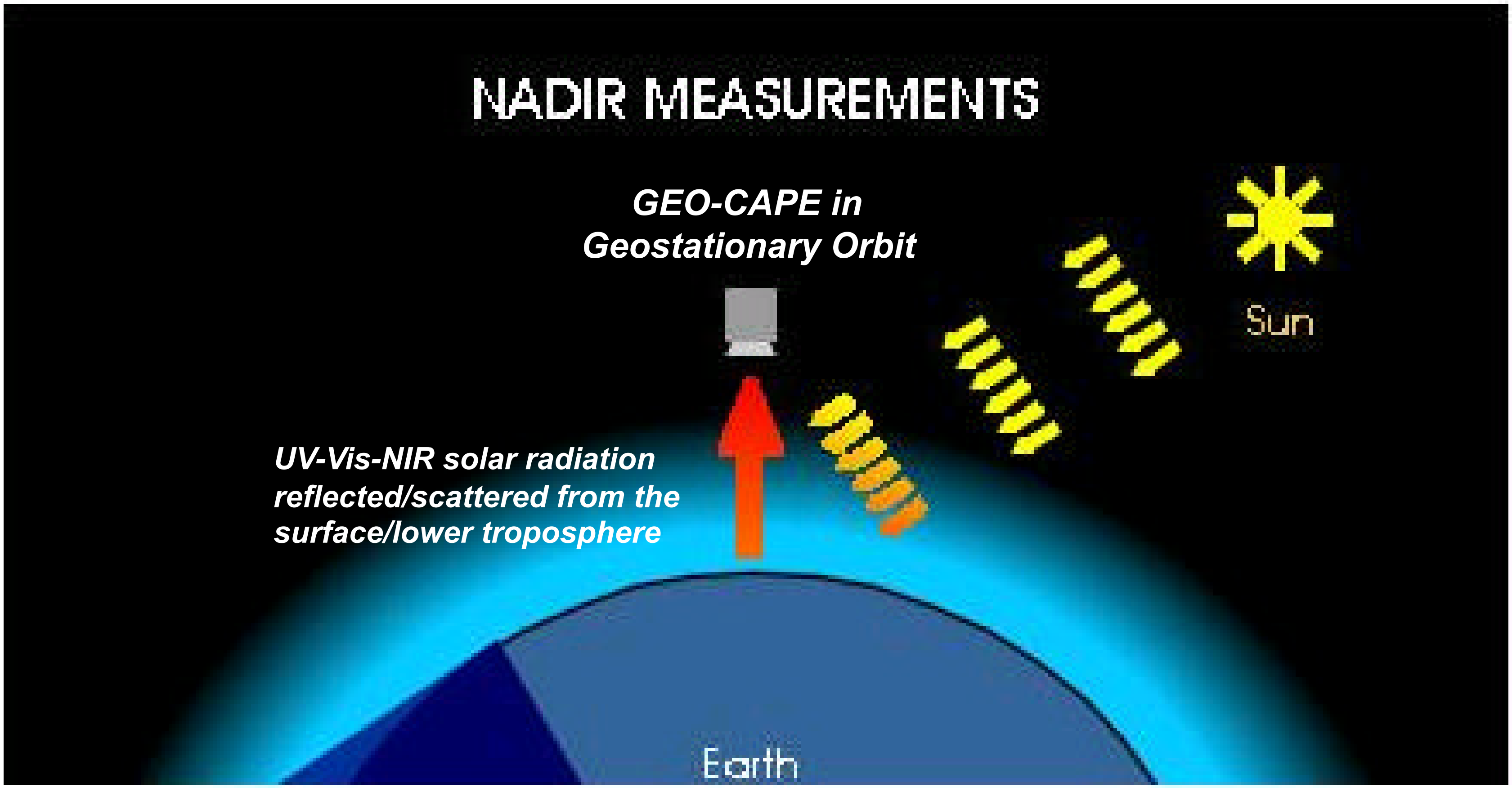
- Temporal sampling sufficient to resolve processes in coastal regions which are dominated by tides and winds (sub-diurnal)



Sept. 2, 2007 12:00:00 *Sept. 4, 2007 12:00:00*

Current imagery like MODIS-AQUA are days apart

Canonical GEO-CAPE DS Mission

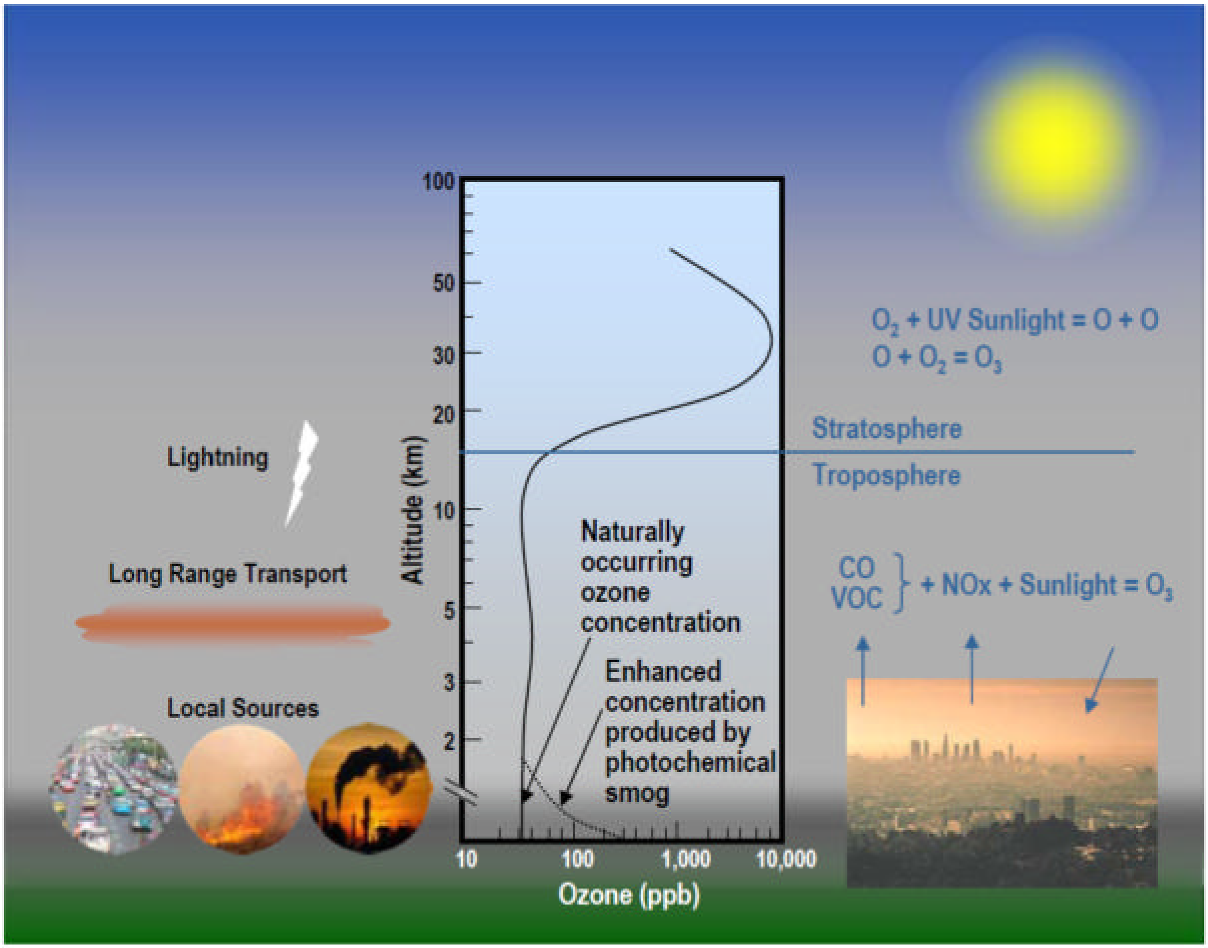


GEO-CAPE Instrument Complement Specified in Decadal Survey

- UV-Vis-NIR wide-area imaging spectrometer for atmospheric composition (O_3, NO_2)
- Steerable 250-m event imaging spectrometer for ocean color
- IR correlation radiometer for carbon monoxide (CO)

adapted from: IUP Bremen

Ozone Vertical Profiles are Crucial



Although ~ 90% of atmospheric ozone is in the stratosphere and only 10% in the troposphere, the tropospheric ozone is important for many reasons including it:

(a) acts as a greenhouse gas and influences the radiative forcing of the climate system

(b) serves indirectly as a 'detergent' that removes gases such as carbon monoxide and methane

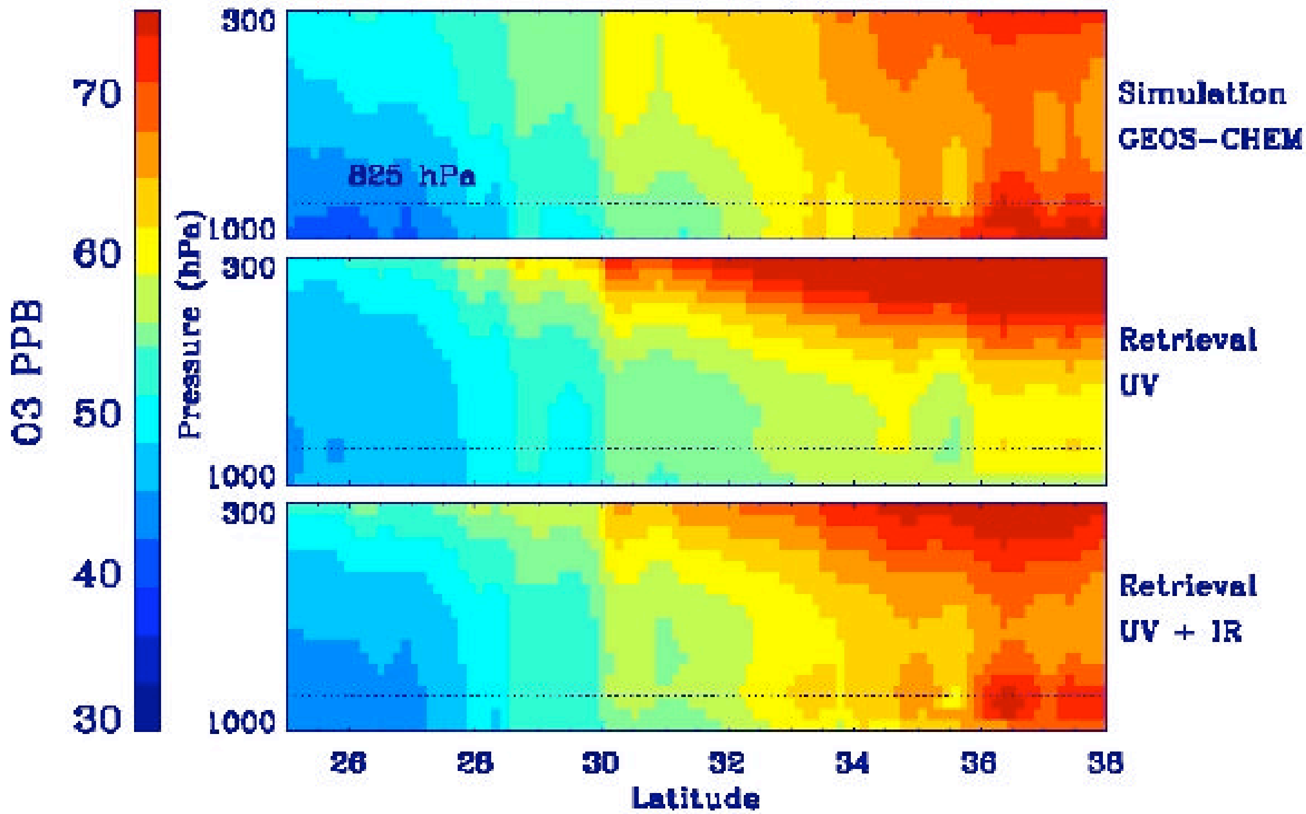
(c) is a pollutant at the surface

Tropospheric ozone profiles are crucial for understanding ozone processes such as production, loss, photochemical, etc.) in:

- vertical transport from the stratosphere
- atmospheric radiative forcing
- long range transport and subsidence
- urban and regional “smog”

Ozone vertical profiles are crucial for understanding ozone processes that impact climate and air quality, and which threaten the public health and welfare of current and future generations

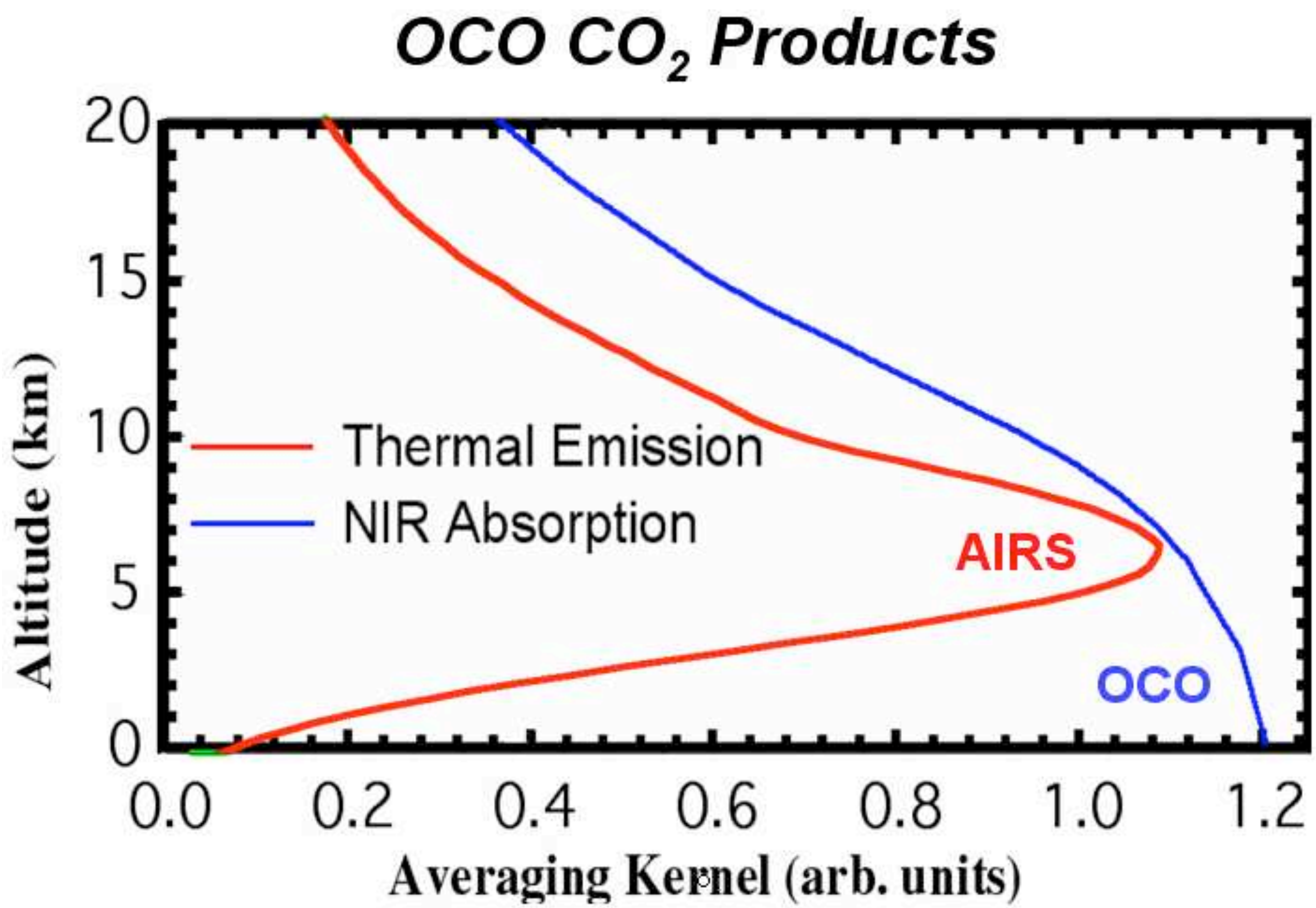
Multi-spectral Retrieval: Enhanced Vertical Profiling of O_3



- Worden et al. (2007)/Landgraf and Hasekamp (2007) showed that simultaneous retrievals using the O_3 9.6 μm and near-UV Huggins Bands increases sensitivity in the boundary layer and lower troposphere

Example: CO_2 Retrieval
TIR (AIRS) and NIR (OCO)

AIRS/OCO Synergy



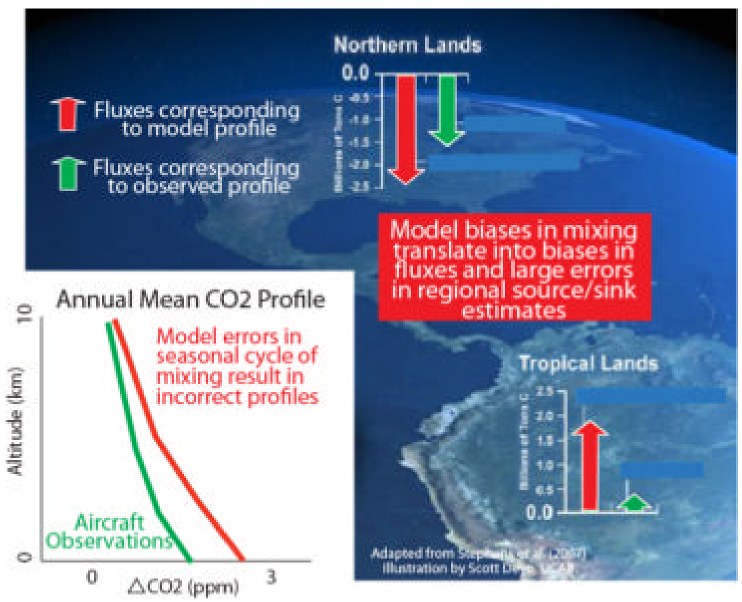
M. Chahine/JPL

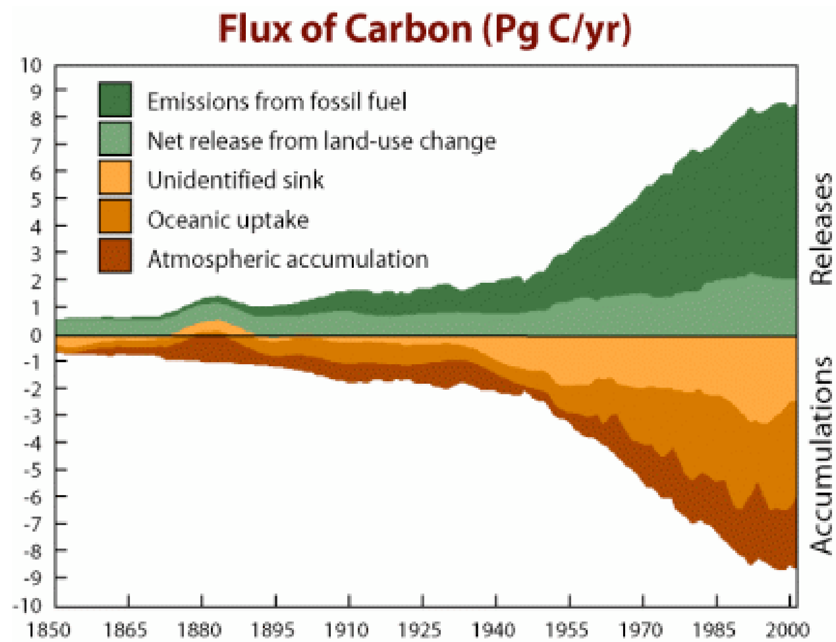
CO_2 Profiles Will Improve Flux Estimates

- CO_2 measured in thermal IR ⇒ sensitive to <u>middle troposphere</u>
- CO_2 measured in near-IR ⇒ sensitive to <u>total column</u>

⇒ Panchromatic retrievals will provide <u>boundary layer</u> information resulting in improved carbon flux estimation:

Simultaneous profiles of HDO, H_2O, CO_2 and CO will reduce CO_2 flux errors arising from sparse characterization of boundary layer transport.





Hourly panchromatic measurements from geostationary orbit will provide the vertical sensitivity and dense sampling of diurnal and seasonal variability needed for atmospheric models to separate surface fluxes from mixing.

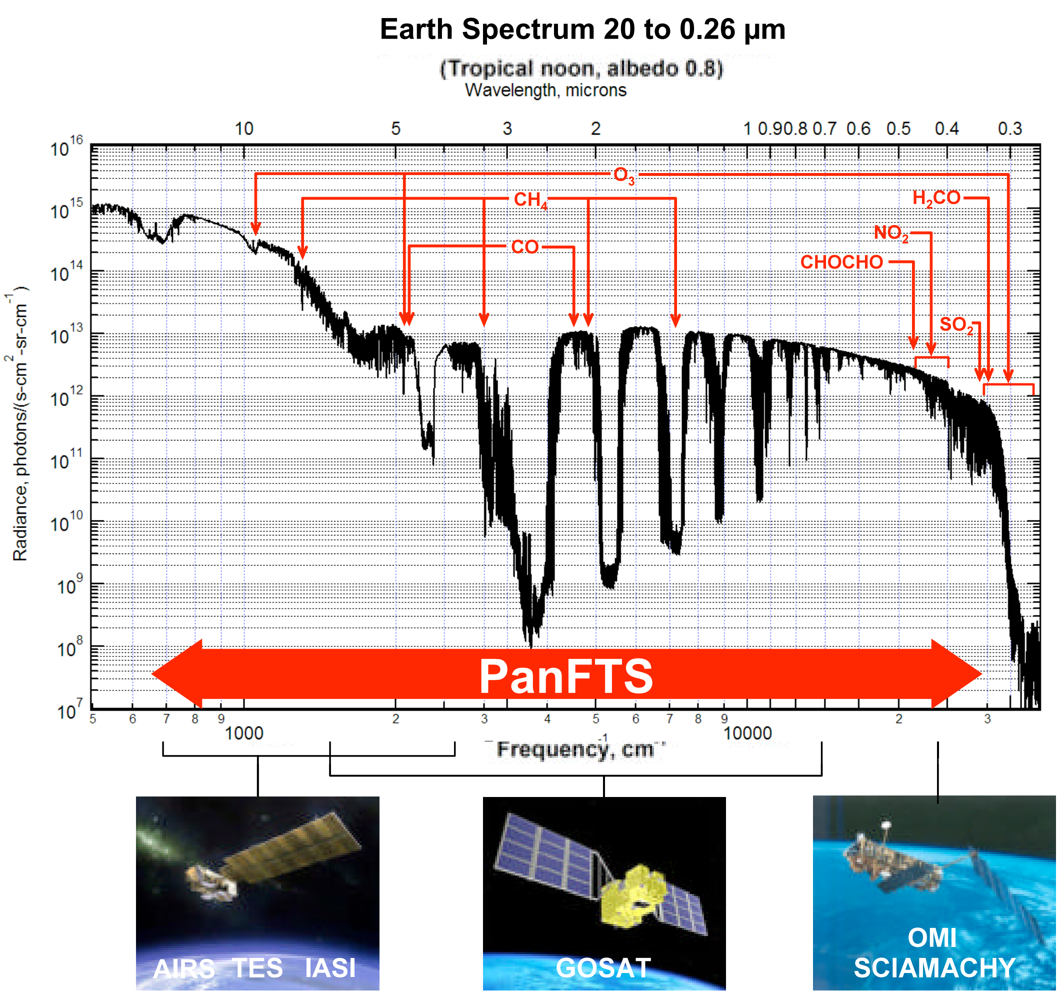
PanFTS Approach to GEO-CAPE Mission

- **Desire**: Expand the science return of the mission beyond the goals in the Earth Science Decadal Survey

- **Approach**: Build a new type of Fourier transform spectrometer with extremely wide spectral coverage (0.26 – 15 μm) and high spectral resolution (0.05 cm^{-1})

- **Benefits:**
  - Significant increase in science return:
  - Wider range of species detected including greenhouse gases, dynamical tracers and hydrological cycle
  - Vertical profiling capability
  - Collapses three separate instruments (UV-vis spectrometer, gas correlation radiometer, ocean color spectrometer) into one.

“Panchromatic” Measurement Approach



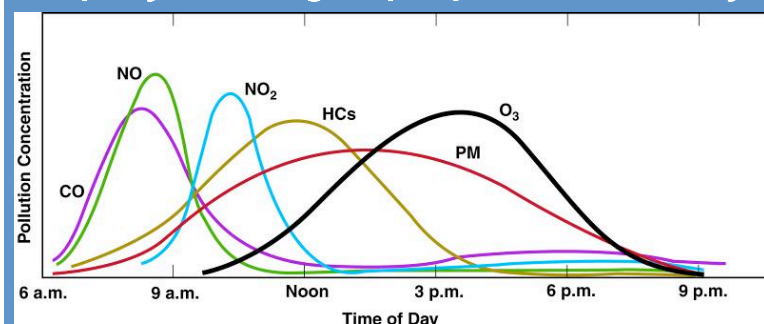
High spectral resolution (0.05 cm^{-1}) and wide spectral grasp (from 14.6 µm to 0.26 µm) allows simultaneous observations of reflected sunlight and thermal emission (day/night) enabling retrieval of several important atmospheric composition species such as

Greenhouse Gases: CO_2, CH_4, N_2O, O_3, H_2O

Pollutants: O_3, NO_2, NH_3, SO_2, HCHO, CH_3OH, CO

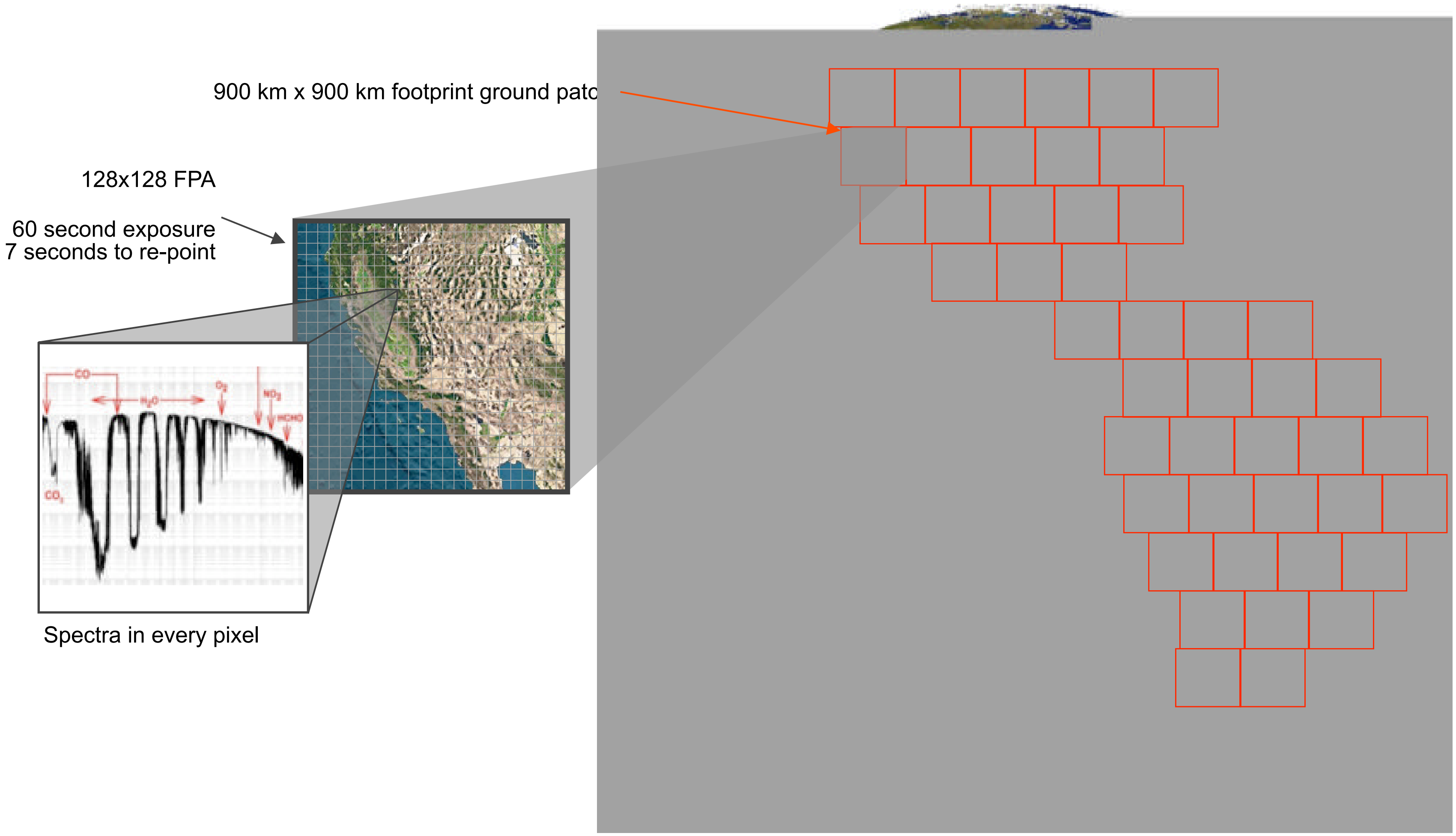
Dynamical Tracers: HDO, N_2O, O_2, O_4

PanFTS high resolution measurements (temporal, spatial, and vertical) will capture rapidly evolving tropospheric chemistry



The wide spectral grasp and high spectral resolution of PanFTS will enable the retrieval of key atmospheric species. Hourly sampling will reveal critical details of chemistry and transport.

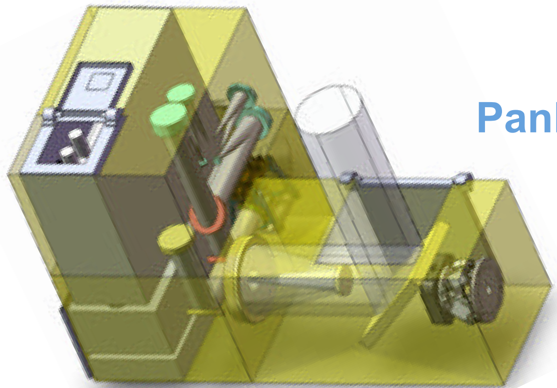
PanFTS Measurement Scenario



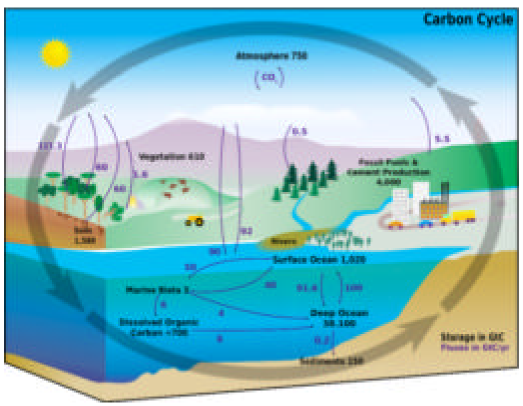
From geostationary orbit, PanFTS wide-field observations can sample ~50 patches per hour with a 900 x 900 km instantaneous field-of-view using a 128 x 128 pixel array which provides a ground footprint with 7 km ground sampling distance per pixel at nadir

Scalable Geostationary Mission Options

PanFTS Wide-Field: 7x7 km²



PanFTS Wide-Field:7x7 km²
PanFTS Narrow-Field: 0.25x0.25 km²



Global Carbon Cycle

Monitor GHG Emission Changes

Air Quality

Coastal Ocean Biogeochemistry

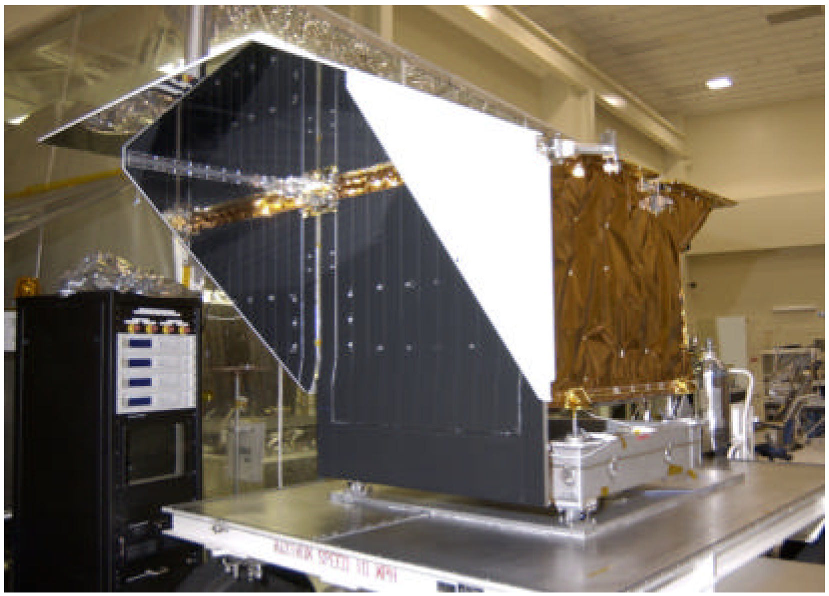
GEO-GHG Mission

GEO-CAPE Mission

The PanFTS instrument can accomplish all of the GEO-CAPE science objectives (atmospheric composition and coastal ocean biogeochemistry) and also map vertical profiles of short- and long-lived greenhouse gases for climate change studies.

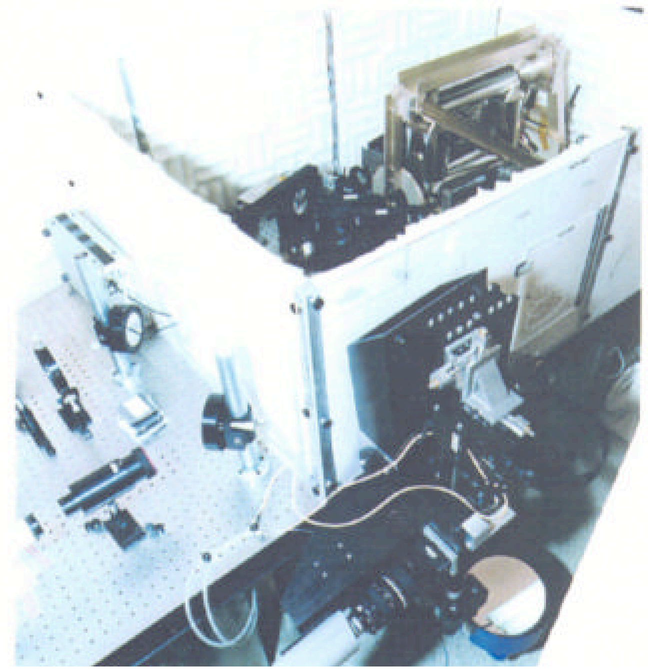
Aura/TES and FTUVS Provide Heritage

Tropospheric Emission Spectrometer (TES)
EOS/Aura



- Cryogenic – 160 K optical bench
- Spectral coverage: 5-15 µm
- Spectral resolution: 0.02 cm^{-1}
- Four 1x16 pixel detector arrays

Fourier Transform UV Spectrometer (FTUVS)
JPL Table Mountain Facility



- Spectral coverage: 0.25-2.5 µm
- Spectral resolution: 0.06 cm^{-1}
- Parallelogram/flexure mechanism with voice coil actuator

PanFTS Laboratory Development Programs

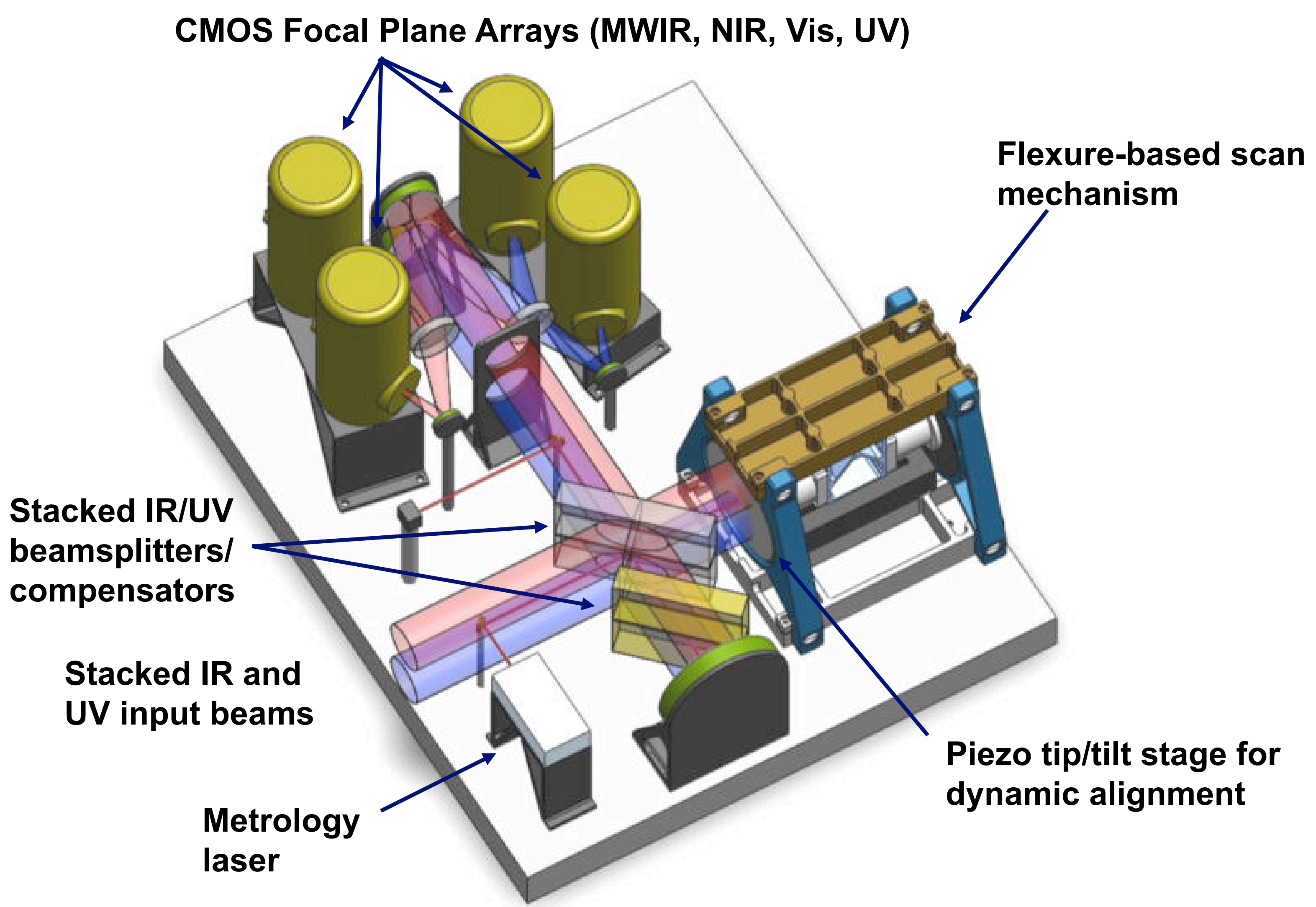
▪Instrument Incubator (Sept. ’08 start, 3-year duration)

- Lab FTS to demonstrate broad spectral grasp
- Field demonstration at JPL’s CLARS Facility at Mt. Wilson
- Key technical challenges:
  - scan mechanism (5 yr life, cold) TRL 4 → TRL 6
  - snapshot FPAs (4x4,fast, high res.) TLR 3 → TLR 4
  - internal and external alignment of two input beams

▪Advanced Component Technology (Jan. ’09 start, 3-year duration)

- 128x128 ROIC with in-pixel ADC
- 16 bit precision @16 kHz frame rate

PanFTS Instrument Architecture

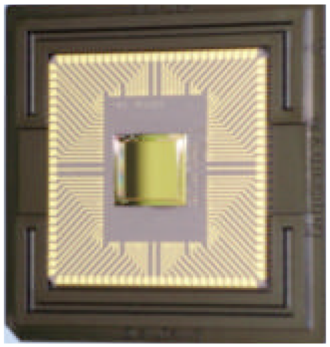


Key FPA Requirements

FPA Characteristic	MWIR	SWIR	VISIBLE	UV
Spectral Range	14.6 to 3 µm	3 to 0.8 µm	0.8 to 0.35 µm	0.35 to 0.26 µm
2D Array Format	≥ 128 x 128 pixels	≥ 128x128 pixels	≥ 128x128 pixels	≥ 128x128 pixels
Pixel Size	60 µm	60 µm	60 µm	60 µm
Pixel to Pixel Crosstalk	< 1%	< 1%	< 1%	< 1%
Operating Temperature	65 K	65 K	180K	180K
Quantum Efficiency	> 60%	> 60%	> 60%	> 60%
Well Capacity per Sample	$2x10^8$ e^-	$2x10^6$ e^-	$2x10^6$ e^-	$2x10^6$ e^-
Total Noise	<$1x10^3$ e^- per sample	< 50 e- per sample	< 50 e- per sample	< 50 e- per sample
Maximum bad pixels	< 1%	< 1%	< 1%	< 1%
Nonlinearity	< 0.1%	< 0.1%	< 0.1%	< 0.1%
Readout Mode	Snapshot	Snapshot	Snapshot	Snapshot
Read Out Frame Rate	≥ 8 kHz	≥ 8 kHz	≥ 8 kHz	≥ 8 kHz
Frame Integration Time	$1x10^{-4}$ seconds	$1x10^{-4}$ seconds	$1x10^{-4}$ seconds	$1x10^{-4}$ seconds
ADC Resolution	16 bits	14 bits	14 bits	14 bits
Integration Time Precision	1 part in 2^{16}	1 part in 2^{14}	1 part in 2^{14}	1 part in 2^{14}
Total Power Dissipation	< 1W	<1 W	<1 W	<1 W

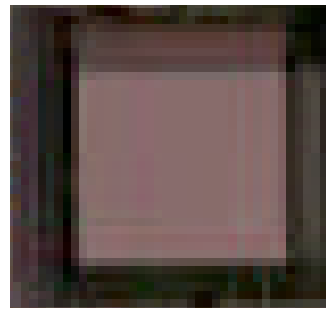
IIP and ACT FPA Evolution

IIP InSb Detector Array (IR)

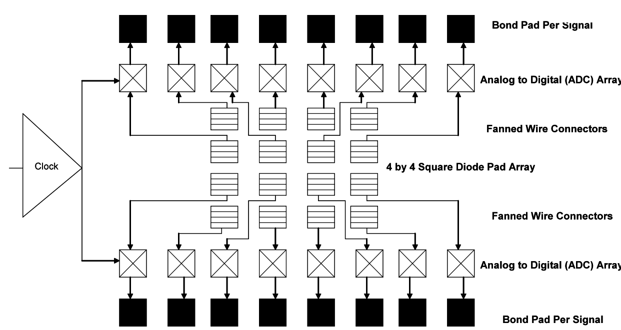


- 256x256 Raytheon InSb
- Analog output
- Off-Chip ADCs
- Lab testing now

IIP Si Detector Array (UV-Visible)

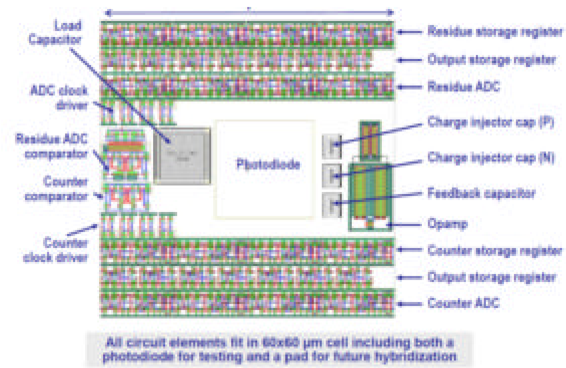


- 4x4 UV-Vis HyViSi detector
- Will be hybridized to JPL ROIC
- One on-chip Σ-Δ ADC/pixel
- ROIC is currently in test



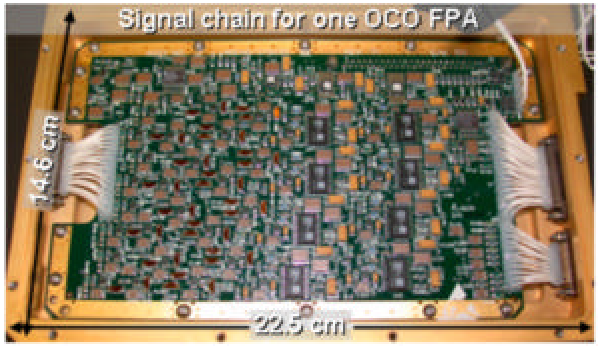
ACT In-Pixel ROIC

- One ADC/pixel: 128x128 format
- On-Pixel ADC
- Released to foundry for fab.
- Major step forward in ROIC development

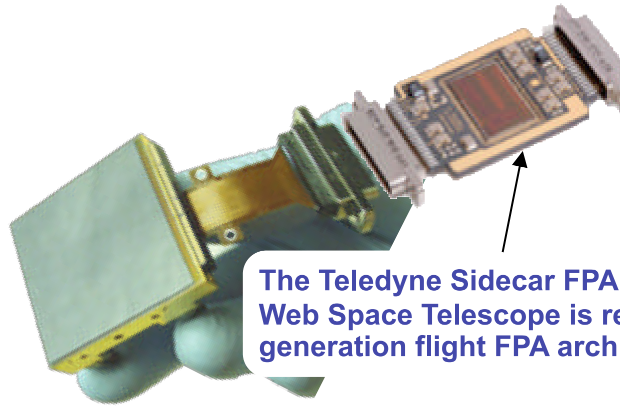


Note: Hybridization of the ACT ROIC with an IR or UV-Vis array is currently unfunded.

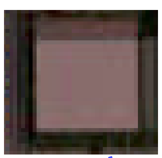
FPA Technology Advancement



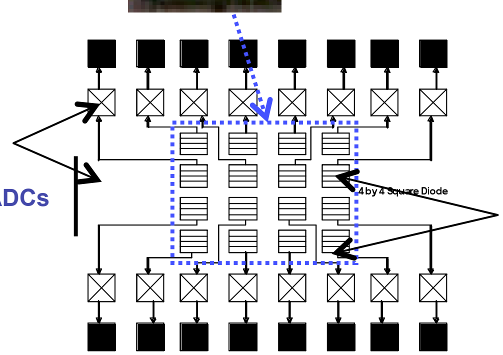
The Orbiting Carbon Observatory FPA signal chain is representative of current flight FPA architecture technology



The Teledyne Sidecar FPA signal chain for the James Web Space Telescope is representative of next generation flight FPA architecture technology

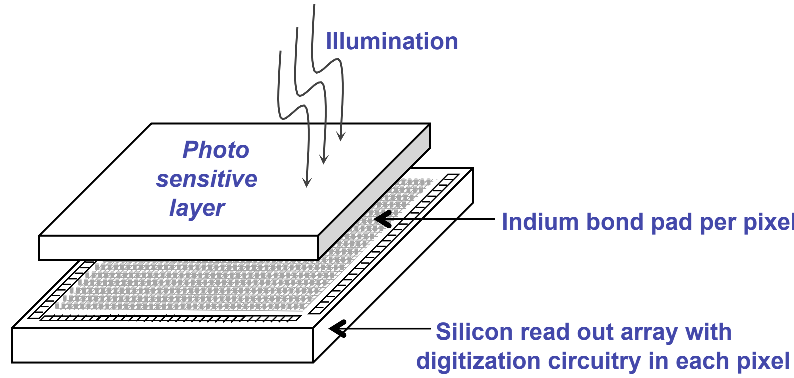


The PanFTS FPA signal chain has the photosensitive layer bonded to a CMOS ROIC array with a separate ADC for each pixel



CMOS Read Out Integrated Circuit

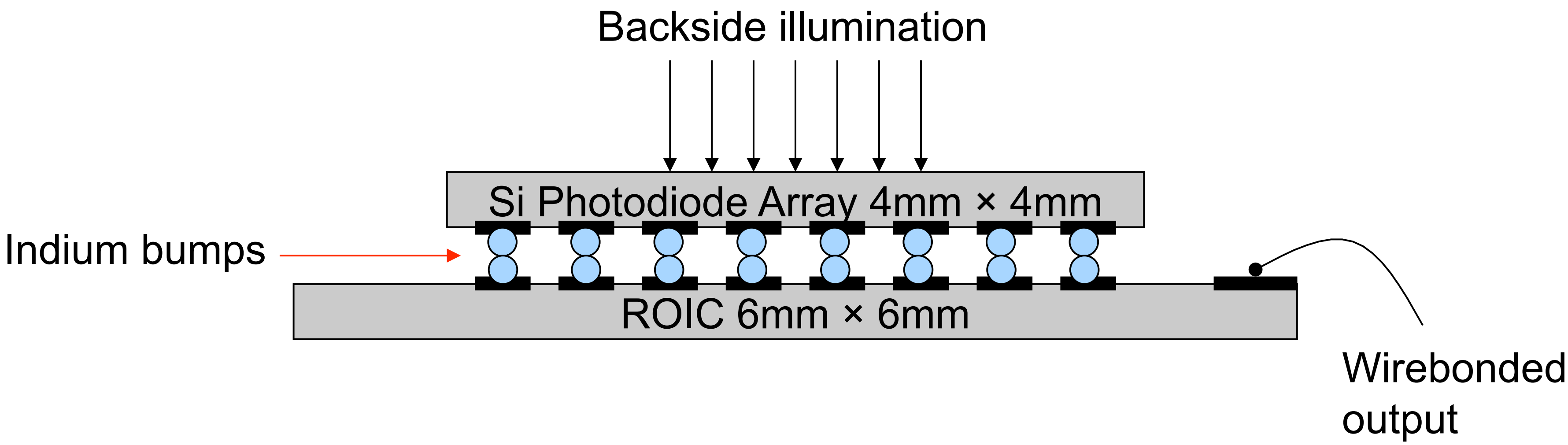
ACT FPA



The JPL In-Pixel Digitization ROIC FPA* has an ADC in every pixel which enables very high speed, high precision read out performance

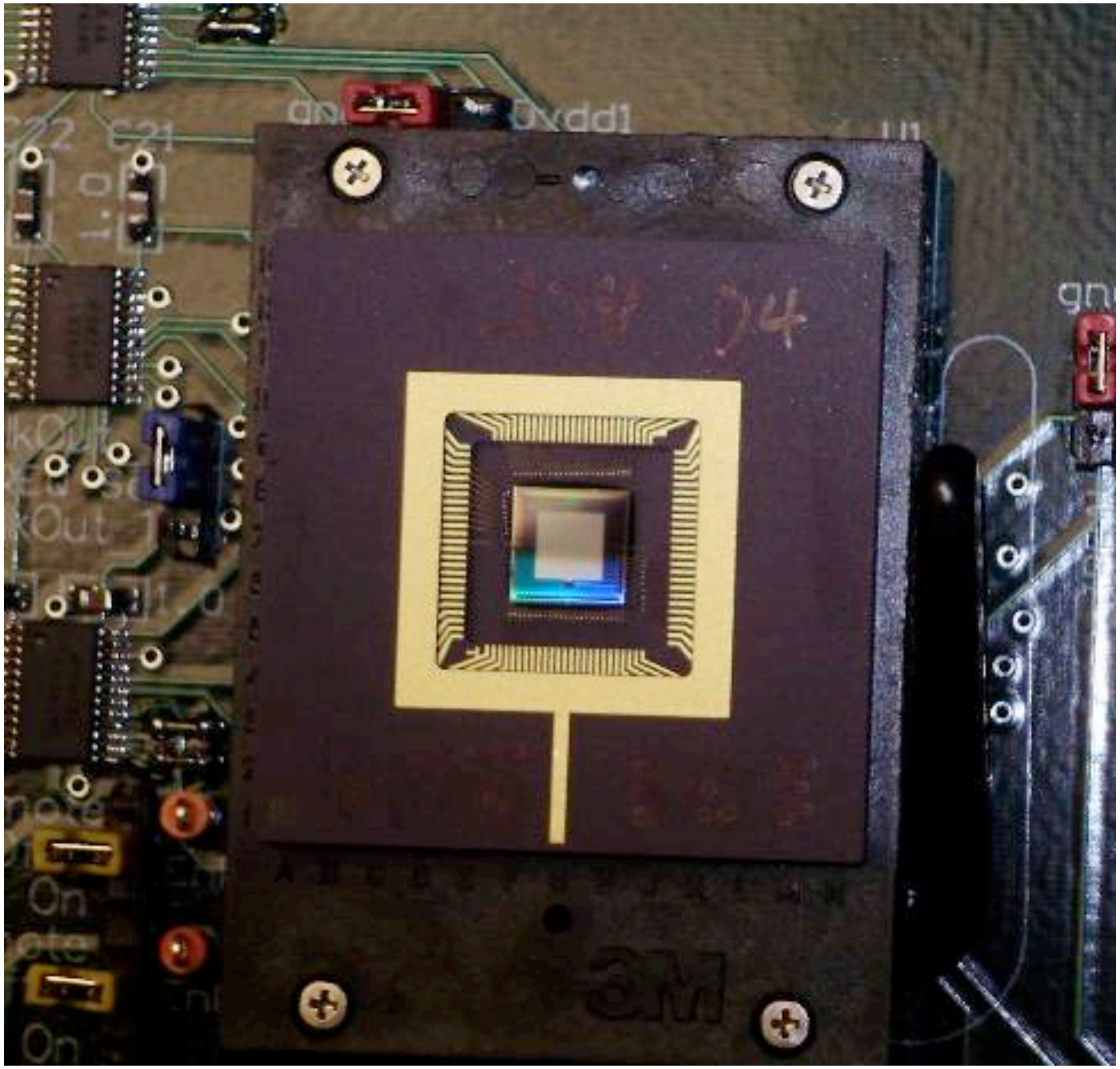
* this development is funded by the ESTO ACT Program

PanFTS Visible FPA Architecture



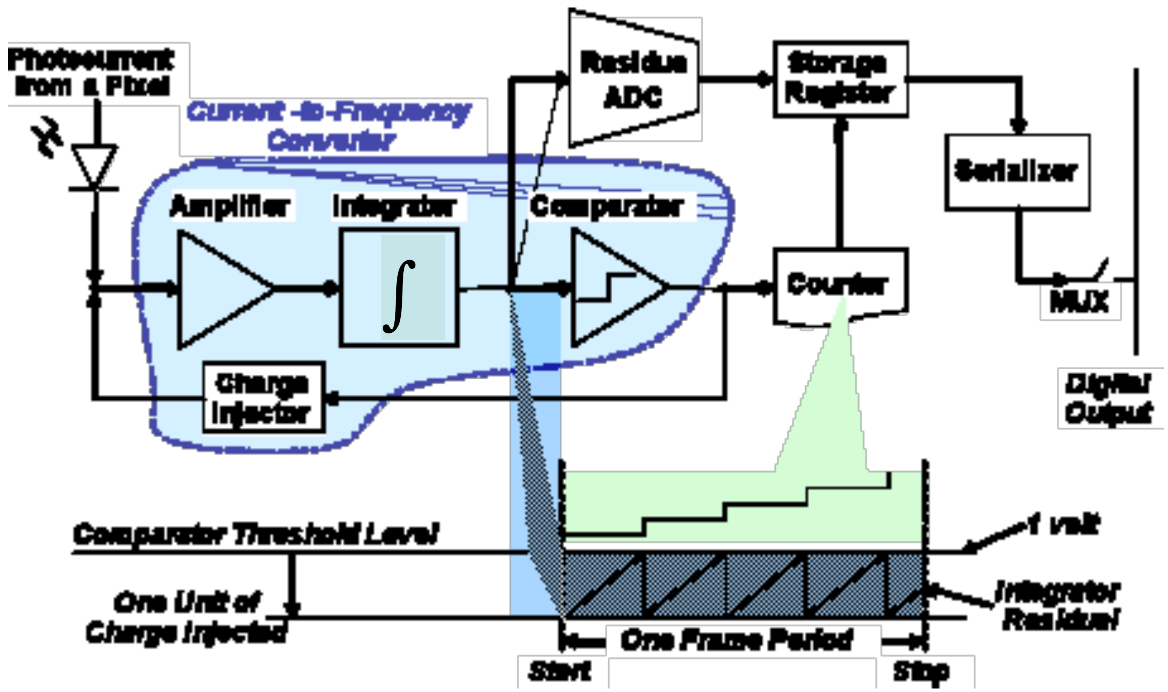
- FPA is a hybrid consisting of a Teledyne silicon photodiode array bump-bonded to a custom Read-Out Integrated Circuit (ROIC).
- ROIC is a 4x4 array of delta-sigma analog-to-digital converters.
- The silicon array is sensitive over the 0.3-1 μm spectral region.
- When completed, the FPA will have sufficient precision (14 bits) and speed (16 kHz frame rate) to meet the requirements of the PanFTS IIP instrument.

PanFTS 4x4 Readout IC with On-Chip Digitizers

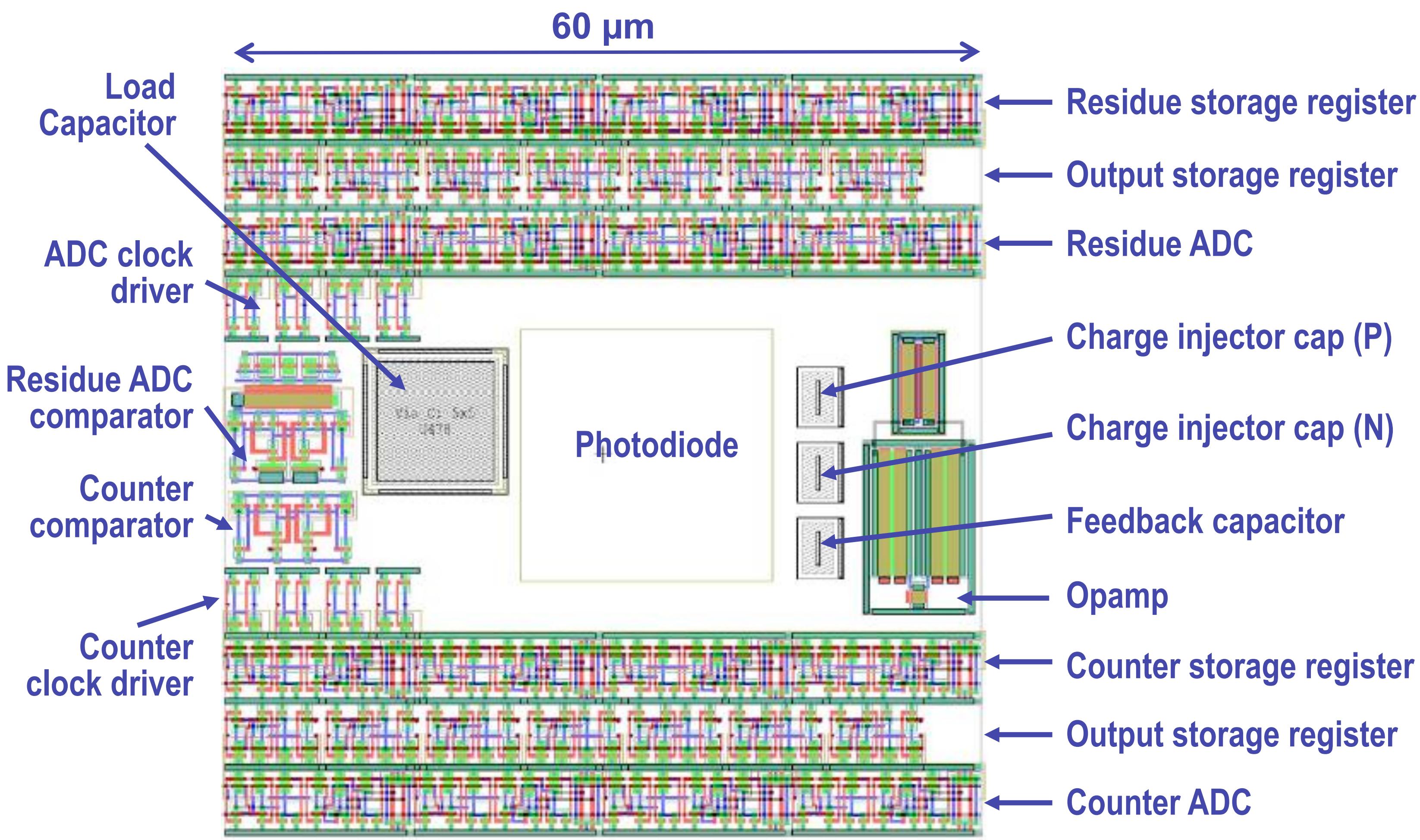


In-Pixel ADC Circuit Architecture

- Technical Challenges
  - Massively parallel ADC architecture (16,384 identical independent ADCs)
  - New unit cell ADC design with wide dynamic range (integrator/residue)
  - Resolution up to 16-bits
  - Full frame read out at 16 kHz rate
  - Circuit footprint that fits within pixel area (60x60 μm^2)
  - Total array power dissipation < 2W
  - Common circuit design that works with UV-Vis and IR detector arrays

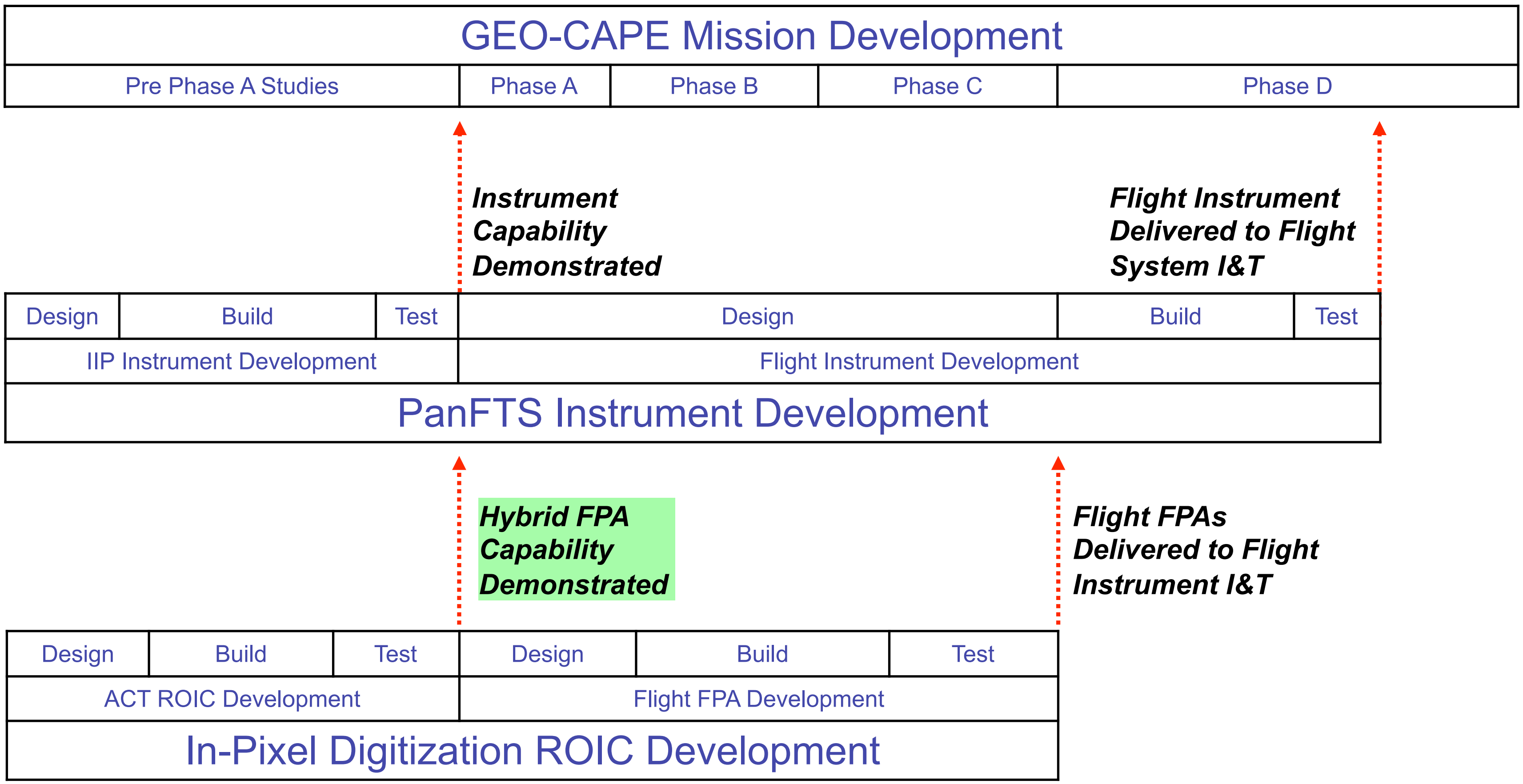


Pixel Layout



All circuit elements fit in 60x60 µm cell including both a photodiode for testing and a bond pad for hybridization

Advanced ROIC Technology Infusion

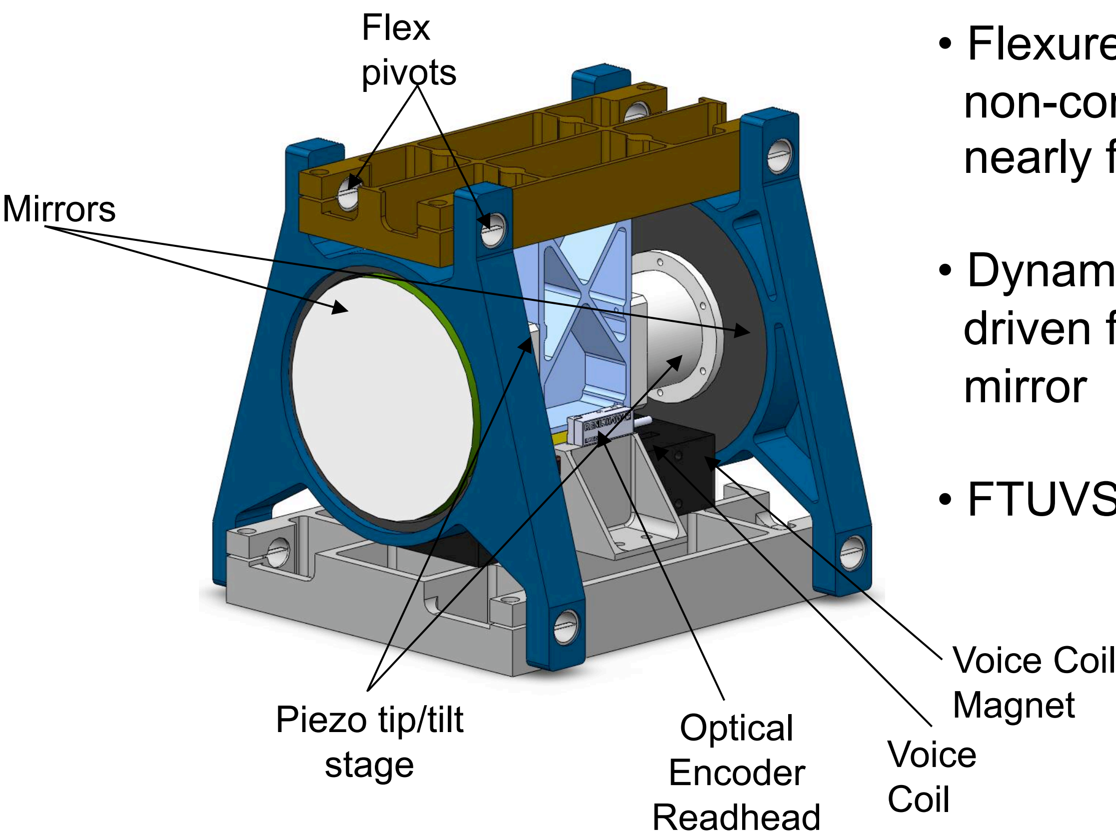


Flight OPD Mechanism Specifications

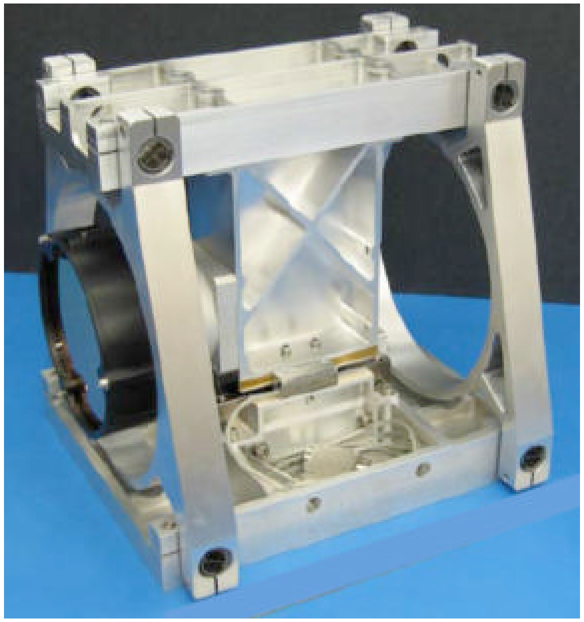
Requirement	Value	Rationale
Provide optical path difference	10 cm	Enables spectral resolution of 0.05 cm^{-1}
Translate mirror	12 cm diameter flat mirror	Accommodates two stacked 5 cm diameter beams plus 0.5 cm optical beam divergence
Mirror surface flatness	Lambda/10 overall; lambda/20 for UV area	Provides high UV modulation efficiency
Range of on axis linear translation	5 cm	Provides 10 cm of optical path difference
Mirror tip/tilt angle (dynamic alignment ON)	< 1.0 µrad with a spectrum distribution in 1/f	Provides UV modulation efficiency of 87%
Mirror tip/tilt angle (dynamic alignment OFF)	< 1.0 mrad	Stay within range of dynamic alignment system
Full translation duration	1 minute	Hourly coverage of 50 ground patches
Mechanical translation velocity	0.0833 cm/s (5 cm / 1 minute)	One minute observation of each ground patch
Mechanical translation velocity stability	< 1% over the full range of travel with a spectrum distribution in 1/f	(Negotiable) No resonances, no high frequencies
Duty cycle	99%	Bidirectional operation (FWD+REV)
Fundamental resonant frequency	> 100Hz	Minimize susceptibility to ambient vibrations
Operating temperature	180K to 320K	Minimize instrument thermal IR emission
Operation unaffected by gravity	0 to 1 G over inclination of zero to 5 degrees	Allows operation in aircraft environment
Operational lifetime	5 years continuous cycling (~ 2.6 million cycles)	GEO-CAPE mission duration
Overall size	25h x 25w x 31 cm translation axis	Remain commensurate with mirror size

Legend: PanFTS driving performance specifications

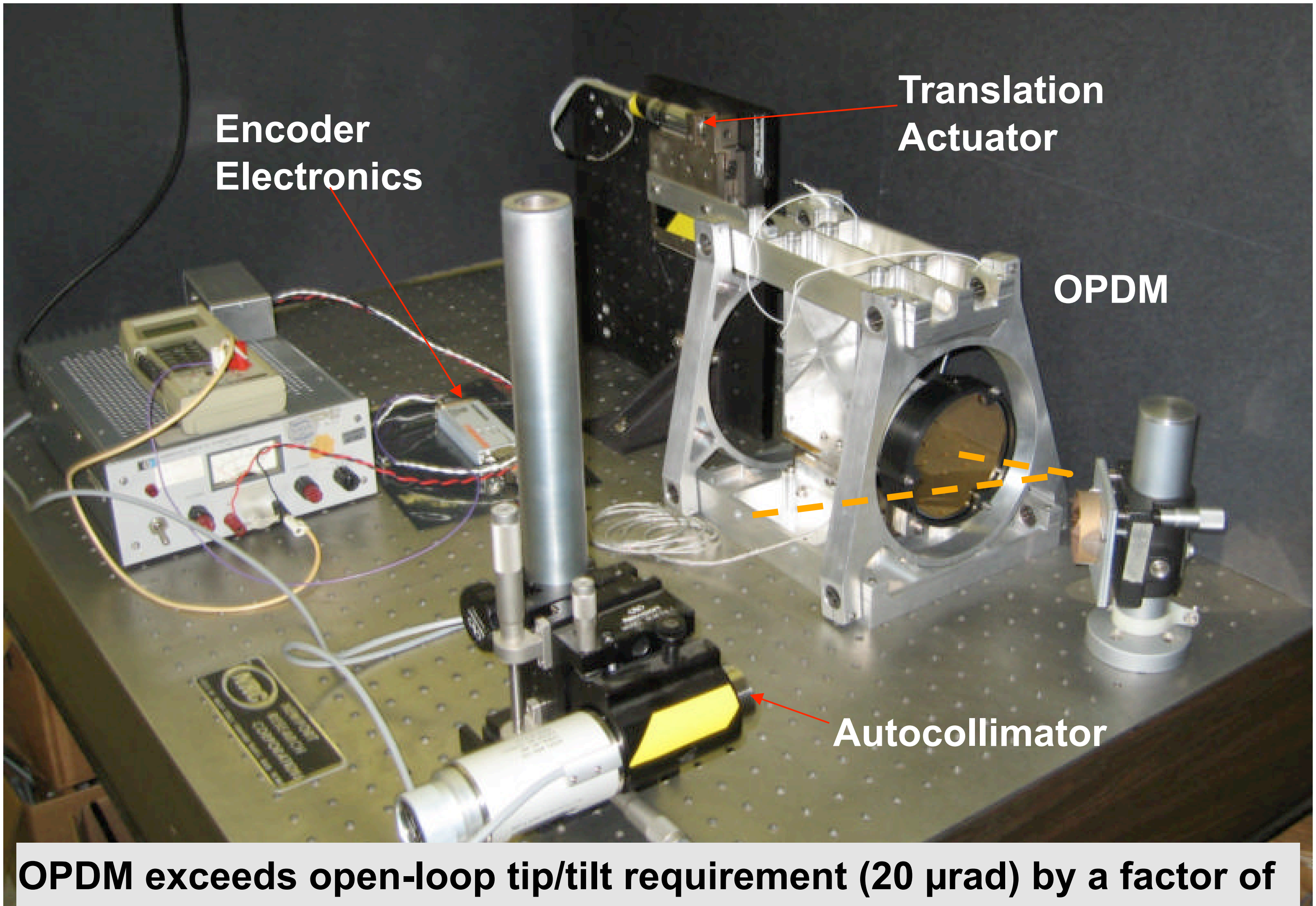
PanFTS Optical Path Difference Mechanism



- Flexure-based four-bar linkage with non-contact voice coil actuator for nearly frictionless operation
- Dynamic alignment using piezo-driven flexure stage on moving mirror
- FTUVS heritage

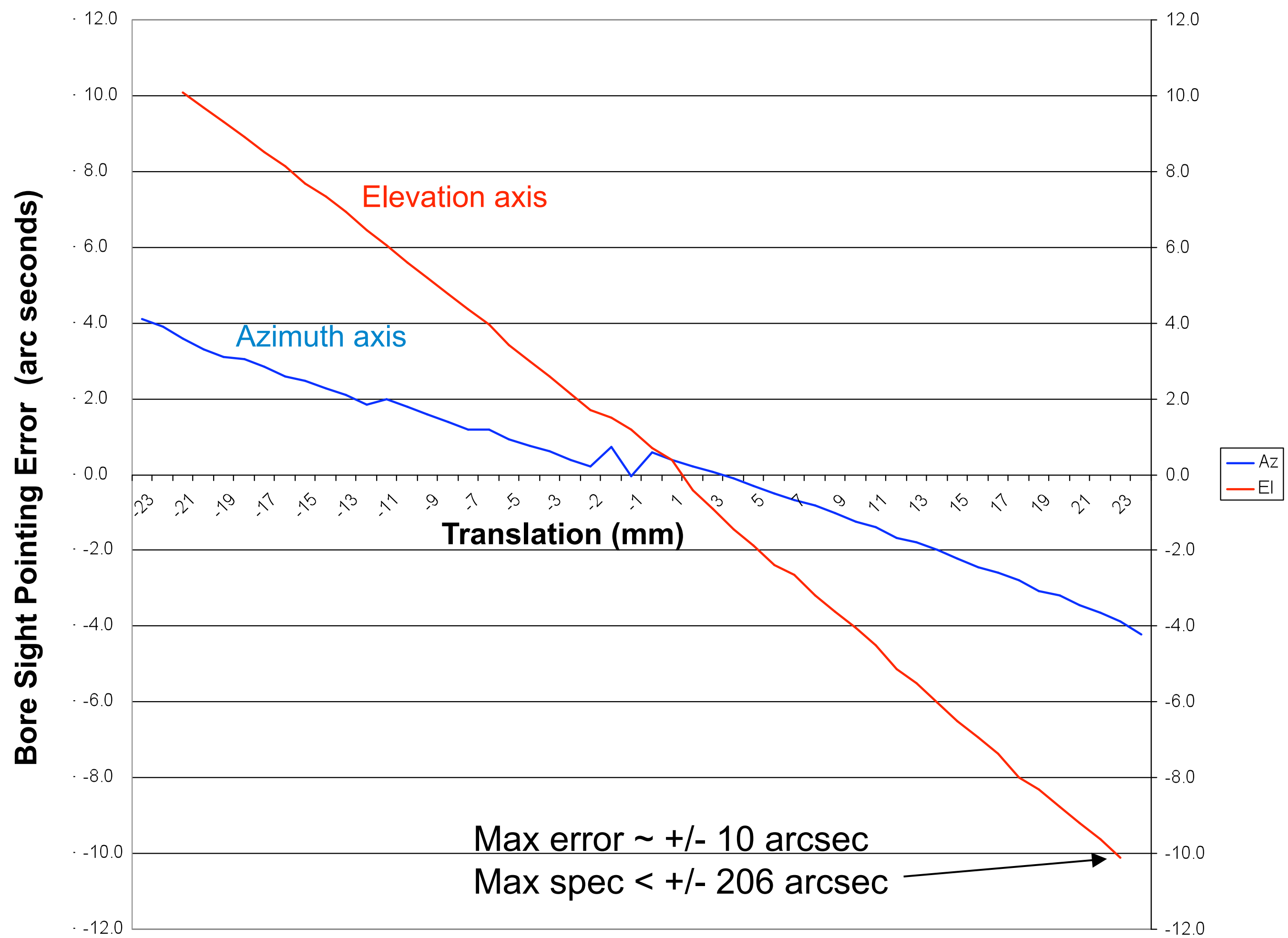


OPDM Mechanical Alignment Testing



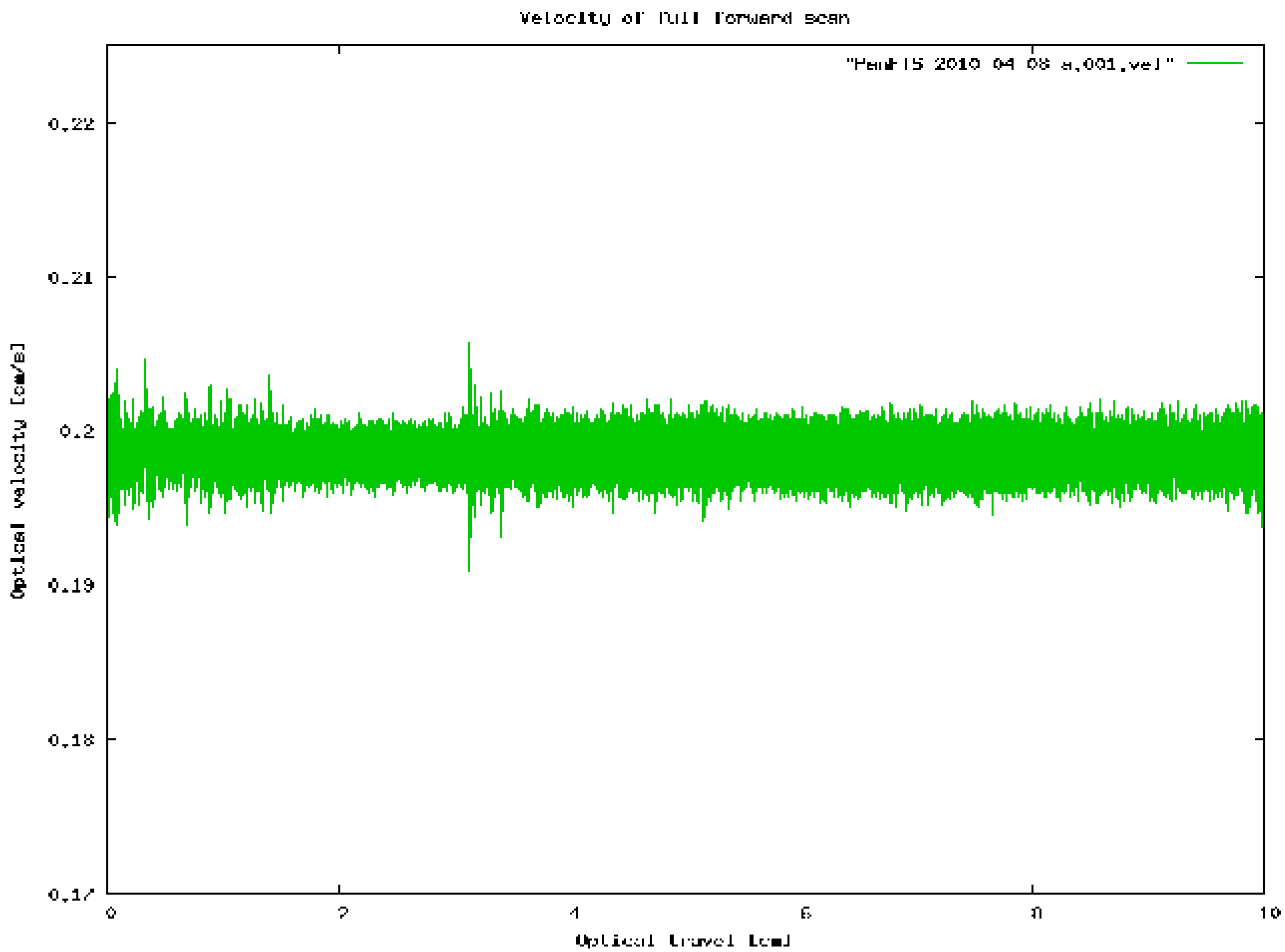
OPDM exceeds open-loop tip/tilt requirement (20 µrad) by a factor of 2

OPDM Open Loop Tip/Tilt Performance



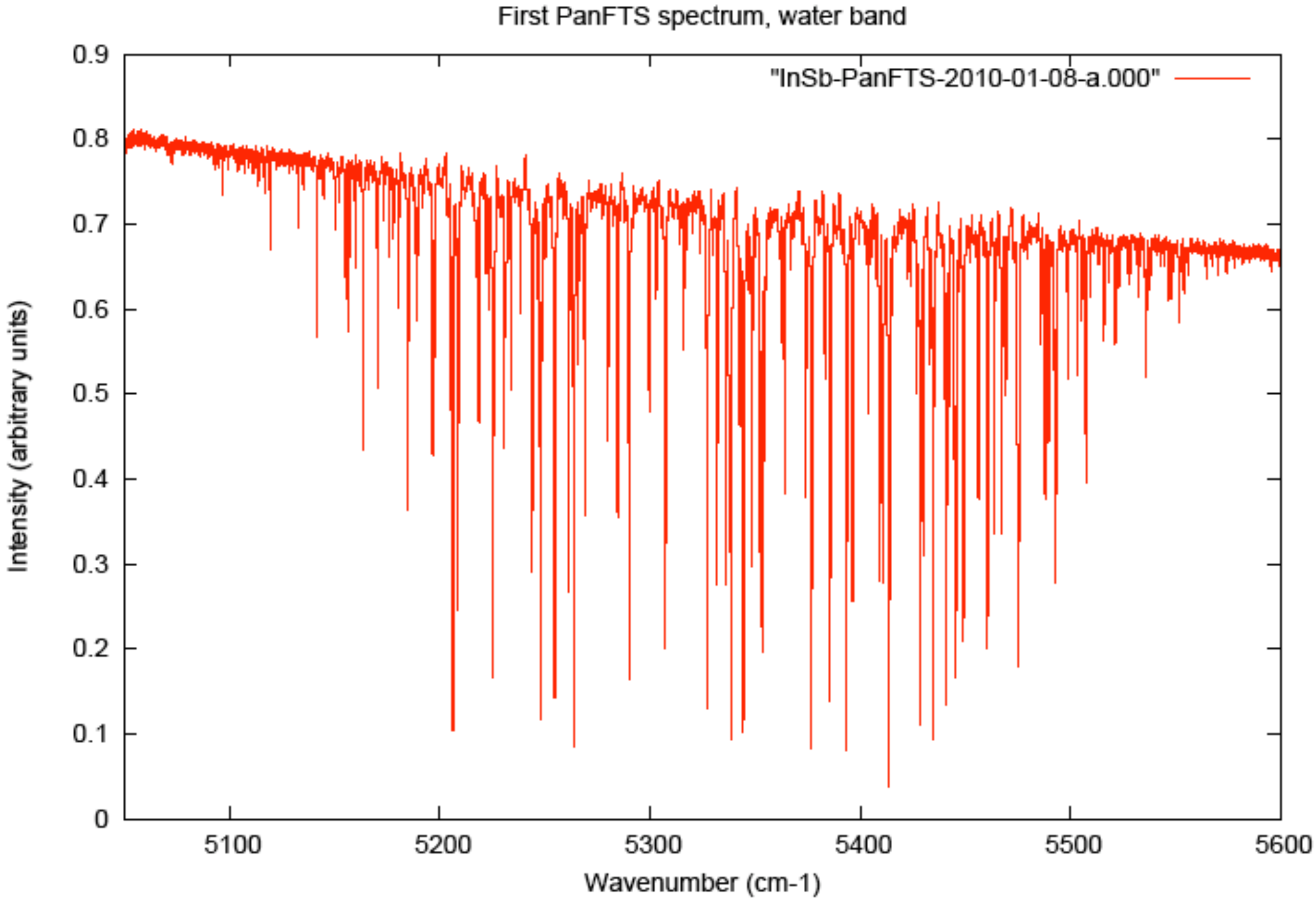
Open-loop tip/tilt performance exceeds requirement by factor of 20

OPDM Dynamic Performance



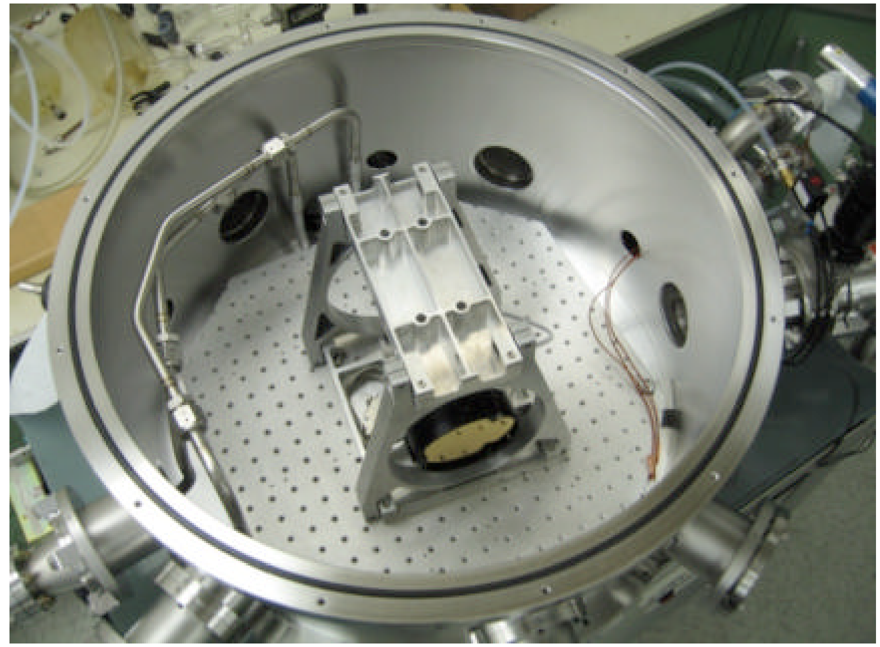
Test results show the OPDM velocity stability error was 0.60 % RMS over the 10 cm travel which is excellent and well below the 1.0 % design requirement

OPDM Dynamic Performance (Dynamic Alignment Off)



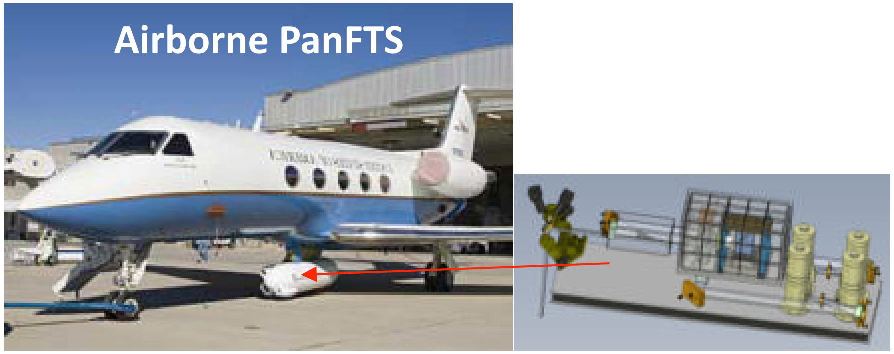
The narrow spectral lines seen in the spectrum of ambient water vapor confirms the OPDM has excellent mechanical alignment performance

OPD Mechanism Life Test Chamber



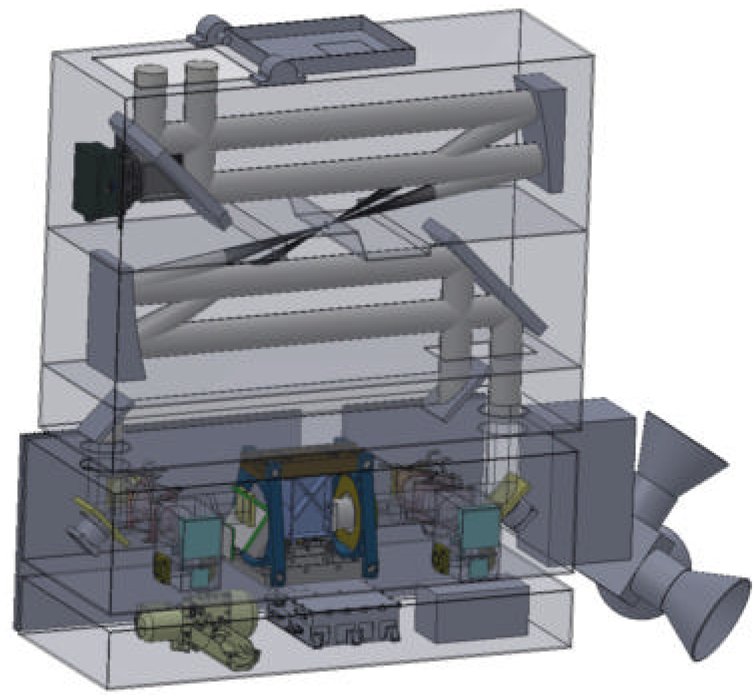
- Vacuum system check out completed
  - Vacuum test achieved 3.6 x 10-6 torr
- Cryo system tests underway with new coolant hoses
  - Expect 208K to 184K performance
- Life test OPDM in fabrication

PanFTS Development Plans



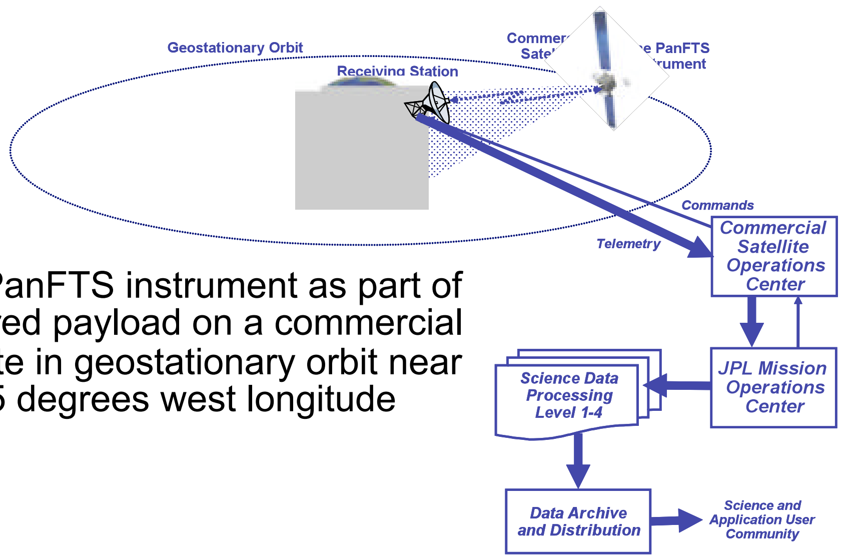
Demonstrate PanFTS atmosphere and ocean science measurement capabilities for GEO-CAPE mission

Engineering Model PanFTS to reduce flight instrument development risks



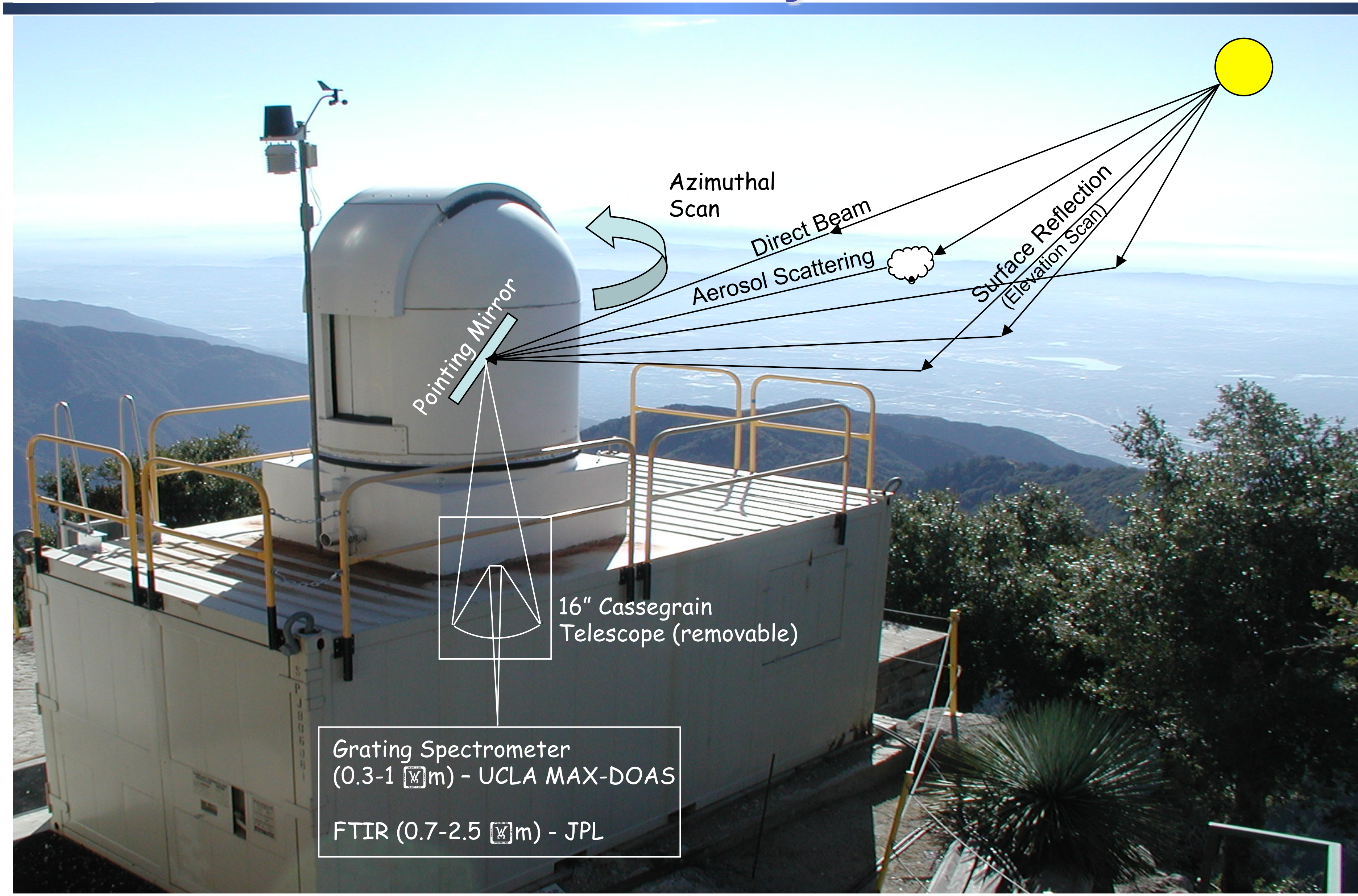
Flight like design that demonstrates flight instrument functions with required operational performance

PanFTS GEO-CAPE hosted payload mission study



One PanFTS instrument as part of a shared payload on a commercial satellite in geostationary orbit near 95 degrees west longitude

“Geo-Like” Trace Gas Measurements from JPL CLARS Facility at Mt. Wilson



Summary

- PanFTS is a major evolutionary step in passive remote sensing of atmospheric composition

- Meets and exceeds the science requirements of GEO-CAPE in a single package.

- Very wide spectral coverage: Mid-IR through UV for vertical profiling of pollutants, greenhouse gases and transport tracers.

- IIP and ACT technology development is on-track
  - Wide-band optical design
  - Advanced digital in-pixel focal plane arrays

PanFTS Team

Stanley Sander, Principal Investigator
Reinhard Beer, Science Plan, Instrument Design
Jean-Francois Blavier, Instrument Scientist
Kevin Bowman, Science Plan
Annmarie Eldering, Science Plan, GEO-CAPE Science Team
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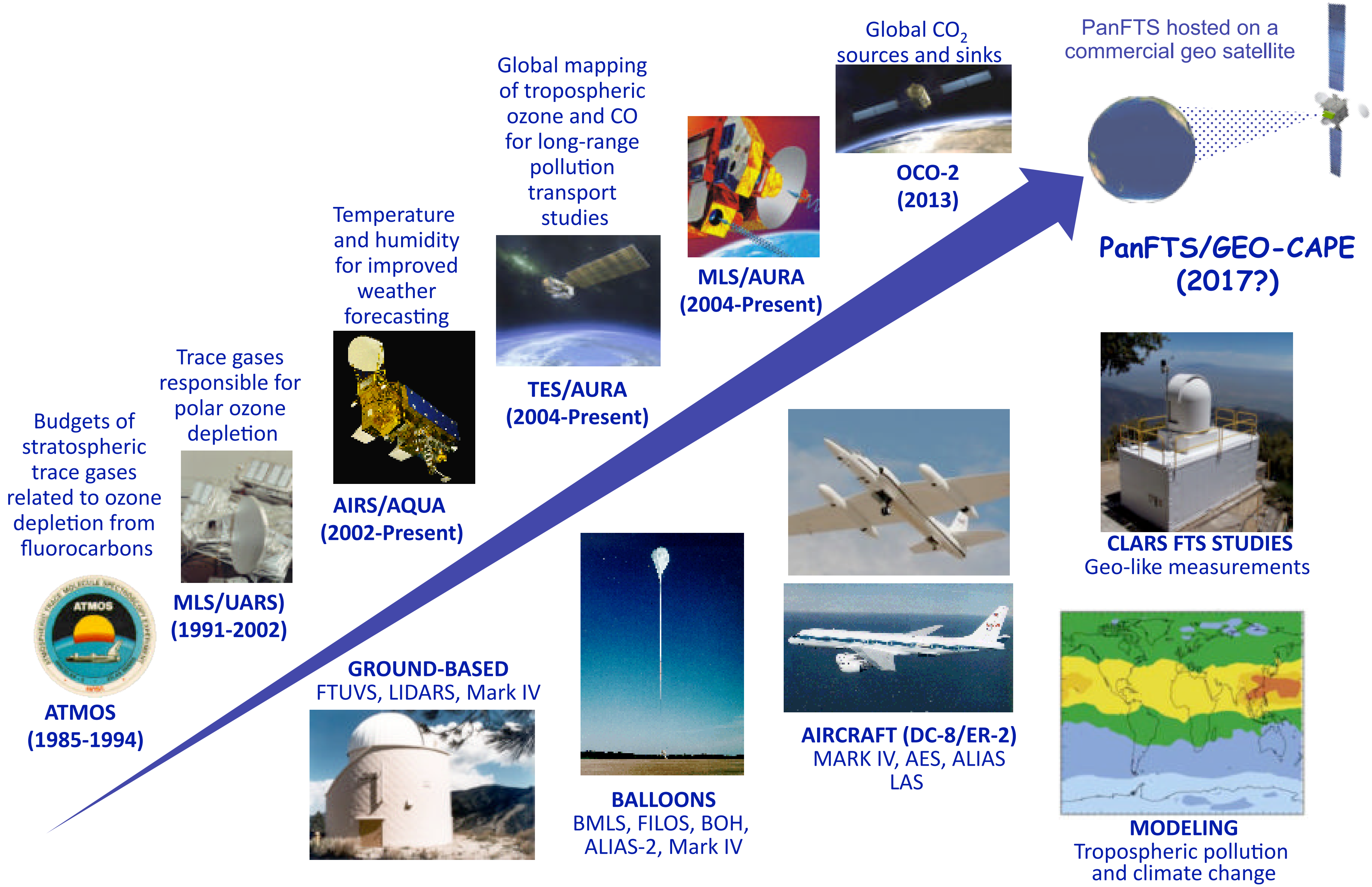
Wesley Traub, Instrument Design
John Worden, Science Plan
Dmitriy Bekker, Command & Data Handling System Development
Matthew Heverly, OPD Mechanism Development
Colin McKinney, OPD Mechanism Development / Analysis
Bruce Hancock, Vis ROIC Development
Tom Lee, Vis ROIC Design & Analysis
Tom Cunningham, Vis FPA Development
James Wu, Optical Design
Bala Balasubramanian, Optics and Coatings
Tim Crawford, Advanced Instrumentation & Spectroscopy Technician
Ken Manatt, Advanced Instrumentation & Spectroscopy Technician
Richard Key, Task Management, Systems Engineering

Thank You!

PanFTS Continues JPL's Role in Atmospheric Composition Science



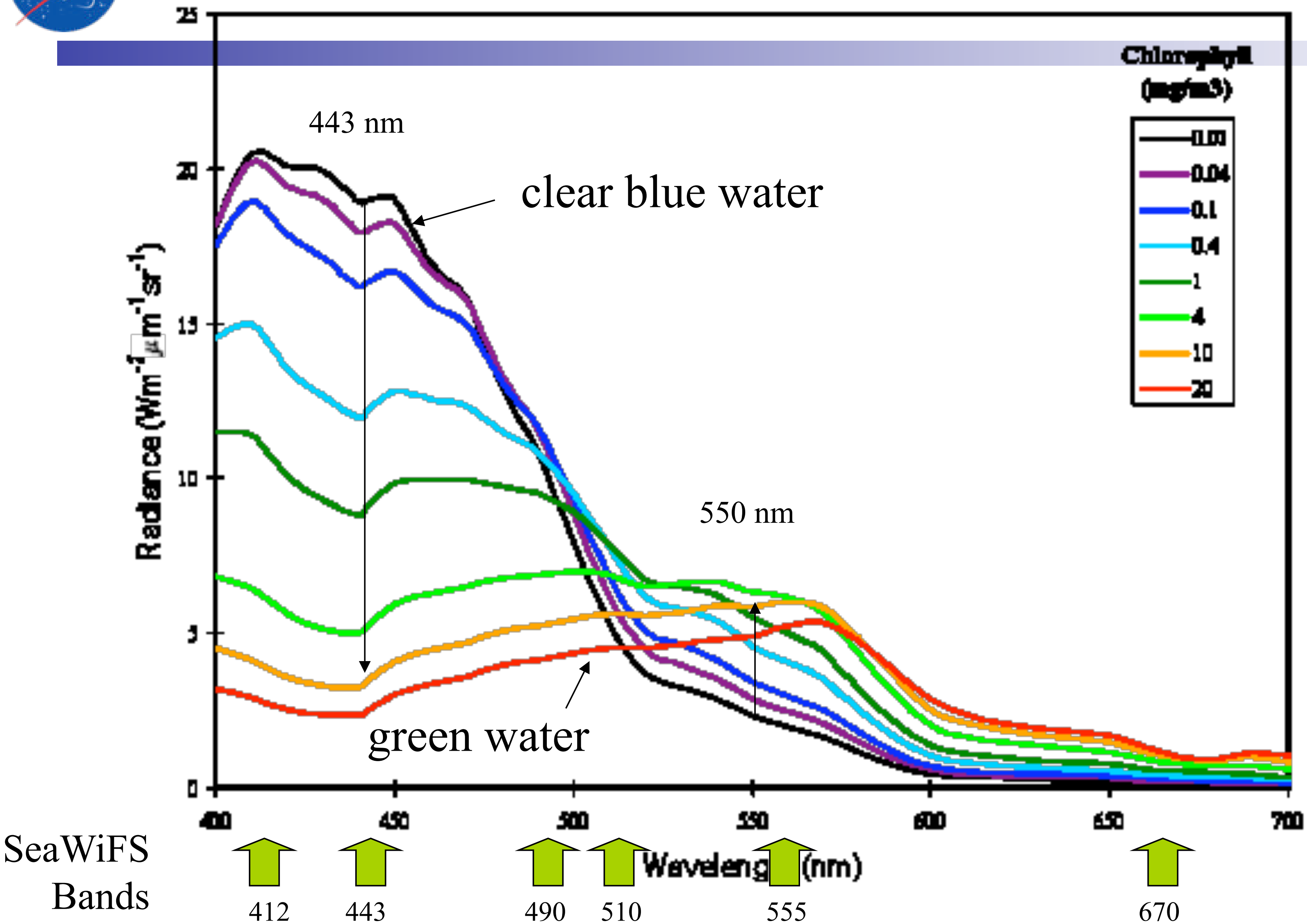
PanFTS IIP Overview

- The Panchromatic Fourier Transform Spectrometer (PanFTS) is a revolutionary new instrument concept capable of measuring atmospheric trace gases, aerosols and ocean color. PanFTS uses imaging Fourier Transform Spectroscopy (FTS) over the spectral range of 0.26 μm to 15 μm enabling simultaneous observations of reflected sunlight and thermal emission (day/night) to measure
  - Pollutants: O_3, CO, NO_2, HCHO
  - Greenhouse Gases: CO_2, CH_4, N_2O, O_3, H_2O
  - Dynamical Tracers: HDO, N_2O, O_2, O_4

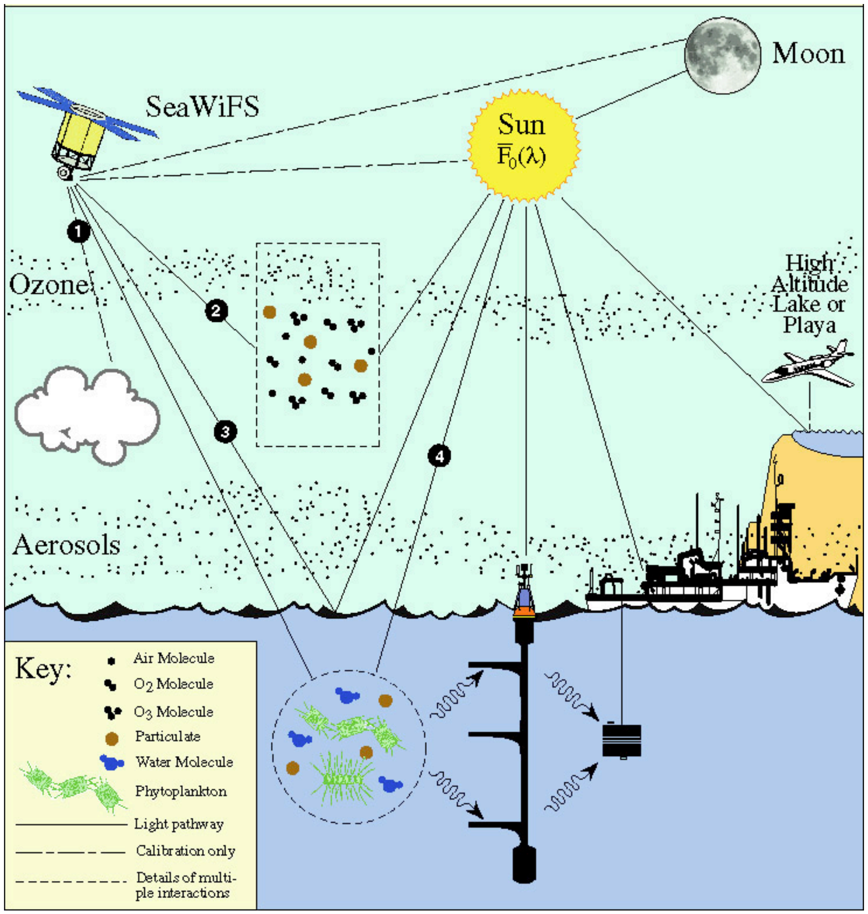
- The PanFTS IIP objectives are:
  - Develop a Science Plan that ensures PanFTS addresses key Decadal Survey measurement requirements and observing scenarios as well as important green house gas measurements that inform climate change models
  - Formulate an instrument design that demonstrates the key features needed for making all GEO-CAPE science measurements
  - Build and test a PanFTS IIP instrument that demonstrates the powerful capability of high resolution imaging spectroscopy to measure atmospheric composition
  - Field test the PanFTS IIP instrument to demonstrate performance by acquiring and analyzing atmospheric spectra viewed from JPL's California Laboratory of Atmospheric Remote Sensing (CLARS) on Mt. Wilson, CA

PanFTS is a very ambitious undertaking

Effect of Chlorophyll on Water-Leaving Radiance



$$\underbrace{L_t(\lambda)}_{\text{1 On Orbit}} = \underbrace{L_r(\lambda)+L_a(\lambda)+L_{ra}(\lambda)}_{\text{2 Atmospheric}} + \underbrace{tL_{wc}(\lambda)+TL_g(\lambda)}_{\text{3 Sea Surface}} + \underbrace{tL_w(\lambda)}_{\text{4 In Situ}}$$



The water-leaving radiance comprises <10% of the top-of-atmosphere signal.

Simultaneous measurements of aerosol extinction, NO_2, O_3 and surface pressure are required to back out the atmospheric contribution to the observed radiance